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CRITERIONS FOR PREDICTION AND CONTROL OF RAM-JET FLOW PULSATIONS

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SUMMARY

The results of a theoretical and experimental study of ram-jet diffuser flow pulsing, commonly referred to as a "buzz condition," with and without combustion are presented herein. The theoretical approach to the problem is a simplified treatment of the ram jet likened to act as a Helmholtz resonator. Experimental verification of the theoretical results was obtained from investigations of various ram jets.

The theory indicated that for the case without combustion a ram jet will resonate if the curve of diffuser pressure recovery as a function of engine mass flow has a positive slope of sufficient magnitude. At operating conditions where the slope of this curve is less than the critical value, the ram jet will not resonate. These theoretical resonance criterions reasonably predicted the occurrence of diffuser-flow pulsations.

For the case with combustion, the rate of heat addition has an important effect in that the ram-jet resonance properties are markedly and complexly altered. In experiments with a 16-inch ram jet, diffuser-flow pulsations occurred with heat addition at conditions where pulsation-free flow was obtained without combustion. The occurrence of these pulsations with heat addition was theoretically predicted on the basis of the resonance properties of the engine. Also presented herein is a discussion of some possible means of eliminating or minimizing diffuser-flow pulsations.

The theoretical resonance frequency for the case without combustion checks the experimental frequency reasonably well both as to magnitude and trend. With combustion, the lowest value of the measured frequency was approximately twice the theoretical fundamental frequency.

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[1]Supersedes NACA RM E51C27, "Criterions for Prediction and Control of Ram-Jet Flow Pulsations" by William H. Sterbentz and John C. Evvard, 1951.

INTRODUCTION

Certain ram-jet supersonic diffusers exhibit pulsating or surging operating characteristics. This condition of operation may occur with or without combustion in the engine. Because of possible serious losses in engine thrust and efficiency (ref. 1), undesirable influences on combustion, or failures in engine or airplane structural members, these pulsations should be avoided. Before beginning a specific discussion of the pulsating characteristics of ram jets, it is advantageous to briefly mention some of the observed properties of ram-jet flow pulsations.

The most commonly observed flow pulsation is the so-called "buzz condition" occurring in ram jets having external compression diffusers either with or without combustion in the engine. This flow pulsation has a frequency range of approximately 1 or 2 to 70 or 80 cycles per second. In some ram jets, these pulsations are manifested over the entire subcritical mass-flow range and for others, only over certain portions of the subcritical mass-flow range.

The occurrence of a "buzz condition" in ram jets with external compression diffusers is related in reference 2 to the presence of a velocity discontinuity downstream of the intersection of two shock waves. Flow fluctuations start when this discontinuity or slip line just enters or leaves the diffuser cowling. Flow pulsations have also been observed concurrently with flow separation from the surface of a diffuser spike, particularly at large angles of attack.

With combustion in the ram jet, flow pulsations may arise from periodic explosions of the fuel-air mixture or from fuel flow pulsations. These pulsations may lead to the generation of lateral or longitudinal waves in the combustion chamber. (See ref. 8.) Any one or all these flow oscillations may occur simultaneously during operation of a ram jet.

The buzz-type flow pulsations have in common at least the following three physical characteristics: (1) The pulsations are characterized by a cyclic rise and fall of pressure within the engine; (2) these cyclic pressure variations occur either with or without combustion in the ram jet; and (3) the frequency and wave characteristics of flow pulsations for a given diffuser are dependent upon the internal geometry of the ram jet. In some cases, the rise and the fall of pressure has a simple sine-wave characteristic and in others, a more complex type of "relaxation oscillation" wave characteristic. These aspects suggest a physical phenomenon following the laws of acoustical resonance.

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Evidence suggesting that consideration should be given an acoustical resonance analysis also lies in the results of work with unsteady operation of compressor-duct systems. The surging of these systems requires that the compressor performance curve (compressor-outlet pressure as a function of mass-flow rate) have a positive slope (ref. 4) and the duct system to which the compressor is connected determines the frequency and the amplitude of the pulsation. The frequency of these pulsations may be theoretically evaluated by assuming that the system acts as a Helmholtz resonator. (See ref. 5.) In fact, reference 6 suggests that a similar criterion might be applied for the occurrence of ram-jet diffuser "buzz." The degree to which the acoustical properties of the ram jet resemble those of either an organ pipe or a Helmholtz resonator, however, may depend on the geometry of the particular unit.

The effect of small flow disturbances on ram-jet diffuser stability has been investigated at the NACA Lewis laboratory using the assumption that the ram jet acts in effect as a Helmholtz resonator. The principles of the conservation of mass, momentum, and energy were applied in a simplified one-dimensional analysis of the resonance properties of ram jets both with and without heat addition. Experimental data from investigations covering a variety of conditions and engine geometries are included as comparisons with the theoretical trends.

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
a	velocity of sound, ft/sec
c_p	specific heat at constant pressure, Btu/(lb)($^{\circ}$F)
f	frequency, cps
H	lower heating value of fuel, Btu/lb
K_1,K_2,K_3	constants
L_C	combustion-chamber length, ft
L_D	diffuser length, ft
M	Mach number

m mass flow, slugs/sec

m_f mass fuel flow, slugs/sec

m_0 diffuser maximum mass flow, slugs/sec

Δm mass-flow perturbation, slugs/sec

P total pressure, lb/sq ft abs

ΔP pressure perturbation, lb/sq ft

R gas constant, sq ft/(sec^2)($^{\circ}$R)

T total temperature, $^{\circ}$R

ΔT temperature perturbation, $^{\circ}$R

t time, sec

u velocity, ft/sec

Δu velocity perturbation, ft/sec

V approximation of effective storage volume of ram jet ($V_T - A_1 L_D$), cu ft

V_C combustion-chamber storage volume between stations 2 and 4 at uniform temperature T_4 for case with combustion or at uniform temperature T_2 for case without combustion, cu ft

V_D diffuser storage volume between stations 2 and 4 at uniform temperature T_2, cu ft (symbol used only in case with combustion)

V_T total volume of ram jet, cu ft

W_A mass of virtual oscillating air column, slugs

W_C mass of gas in ram jet between stations 2 and 4 at uniform temperature T_4 for case with combustion or at uniform temperature T_2 for case without combustion, slugs

W_D mass of gas in ram jet between stations 2 and 4 at uniform temperature T_2, slugs (symbol used only in case with combustion)

γ ratio of specific heats

η_b combustion efficiency

ρ density, slugs/cu ft

τ total-temperature ratio across combustion chamber and outlet nozzle, T_4/T_2

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Subscripts:

0 equivalent free-stream condition

1 diffuser inlet

2 indefinite diffuser station after which velocity perturbations are theoretically considered negligible

3 combustion-chamber outlet

4 exhaust-nozzle outlet

b burning

C combustion chamber

c compression

D diffuser

S stored

x,y area divisions in diffuser at station 2

PULSATION WITHOUT COMBUSTION

Theory

In a continuous, steady-flow ram jet, the diffuser delivers to the combustion chamber an air flow that is exactly equal to the air flow leaving the outlet nozzle. During transient pressure oscillations, however, from whatever the source, the instantaneous air flow m_2 to the ram-jet combustion chamber need not be the same as the instantaneous air flow m_4 leaving the outlet nozzle. Such a condition leads to either a storage or an evacuation of air mass in the combustion chamber. The resonant properties of the ram jet are controlled by the balance between the mass-flow delivery characteristics of the diffuser, the storage capacity of the combustion chamber, and the discharge effectiveness of the exit jet. 2147

Analytical treatment of the exact flow mechanism occurring in the diffuser is complicated by the fact that the air in the diffuser has the properties of both compressibility, thereby including diffuser volume in the storage volume of the ram jet, and inertia, which is assumed to arise from a virtual oscillating air column. In the interests of simplification, the virtual oscillating air column is assumed to have an approximately constant cross-sectional area A_1, and a length extending from station 1 to the indefinite station 2. Thus, except for the exit nozzle, the ram jet resembles a Helmholtz resonator in which an oscillating air column ("air piston") occupies a portion of the diffuser. In a sense, then, the theory implies the existence of a virtual separation of the perturbed flow from the diffuser walls during pulsation. Schematic comparisons of two ram-jet configurations and a Helmholtz resonator showing the assumed air column are given in figure 1.

Conservation of mass through the system requires that

$$\Delta m_2 = \Delta m_4 + \frac{d\,\Delta W_C}{dt} \tag{1}$$

In the analysis, the symbol Δ is used throughout to designate small deviations from mean quantities. The differential equation of the motion is obtained by systematic calculation of the terms in equation (1) as functions of the velocity perturbation of the diffuser air column and the mean flow parameters of the engine.

The perturbed mass-flow rate past station 2 will be the sum of the perturbed mass-flow rates Δm_x through the area of the assumed air column and Δm_y through the residual area at station 2. Thus,

$$\Delta m_2 = \Delta m_x + \Delta m_y \tag{2}$$

The general equation for mass-flow rate is

$$m = \frac{PAu}{RT\left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{1}{\gamma-1}}} \tag{3}$$

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For small deviations (Δ) from the mean quantities, equation (3) may be written

$$\frac{\Delta m}{m} = \frac{\Delta u}{u} - \frac{\Delta T}{T} + \frac{\Delta P}{P} \tag{4}$$

when terms of order M^2 or smaller have been neglected with respect to unity. Consistent with the assumption that the inertia of the flow through A_y changes negligibly, $\Delta u/u$ for this area is omitted. Substitution of equation (4) in equation (2) then yields

$$\Delta m_2 = m_x\left(\frac{\Delta P_2}{P_2} - \frac{\Delta T_2}{T_2} + \frac{\Delta u}{u_2}\right) + m_y\left(\frac{\Delta P_2}{P_2} - \frac{\Delta T_2}{T_2}\right) \tag{5}$$

Even though all globules of the fluid initially have free-stream stagnation temperature, they are submitted to adiabatic compressions during transit through the engine. The changes in stagnation temperature are related to pressure changes by the isentropic relation

$$\frac{\Delta T}{T} = \frac{\gamma-1}{\gamma}\frac{\Delta P}{P} \tag{6}$$

Therefore equation (5) may be stated as

$$\Delta m_2 = m\frac{\Delta P_2}{\gamma P_2} + m_x\frac{\Delta u}{a_2 M_2} \tag{7}$$

In like manner, an expression for the change in mass-flow rate at station 4 arising from a mass-flow perturbation may be derived. By differentiating the general equation of mass flow (equation (3)) assuming choked-flow conditions (constant Mach number, $M_4 = 1.0$) and relating the stagnation-temperature changes to the pressure changes by the isentropic relation given in equation (6), the following expression is obtained for the change in mass-flow rate at station 4: 2147

$$\Delta m_4 = m \frac{\gamma+1}{2\gamma} \frac{\Delta P_4}{P_4} \tag{8}$$

The mass contained in the ram jet between stations 2 and 4 is given by the product of density and volume. Changes in this mass with time may be expressed in terms of combustion-chamber pressure as follows:

$$\frac{d}{dt} \Delta W_C = W_C \frac{d}{dt} \frac{\Delta P_C}{\gamma P_C} \tag{9}$$

Substitution of equations (7) to (9) into equation (1) gives,

$$m \frac{\Delta P_2}{\gamma P_2} + m_x \frac{\Delta u}{a_2 M_2} = \frac{\gamma+1}{2\gamma} m \frac{\Delta P_4}{P_4} + W_C \frac{d}{dt} \frac{\Delta P_C}{\gamma P_C} \tag{10}$$

If the period of oscillation in a ram jet is long compared with the time that is required for a sound or pressure wave to travel across the combustion chamber, the compressions and the rarefactions of the air arising from the unsteady operation of the diffuser may be considered as uniform throughout the combustion chamber. Furthermore, the pressure increments of equation (10) are assumed to consist of two addends, ΔP_I and ΔP_{II}. Thus,

$$\Delta P_2 = \Delta P_4 = \Delta P_C = \Delta P_I + \Delta P_{II} \tag{11}$$

The pressure increment ΔP_I represents the dynamic-pressure increase across the diffuser (stations 1 to 2) associated with the inertia properties of the air and the unsteady operation of the diffuser. The pressure increment ΔP_{II} represents the pressure change in the ram jet due to the diffuser-shock position, which changes during the unsteady operation of the diffuser and will be assumed to be given by the mass-flow change at station 2.

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A simple approximation of ΔP_I may be given by Newton's law

$$\Delta P_I = - \frac{W_A}{A_1} \frac{d}{dt} \Delta u \tag{12}$$

The pressure increment ΔP_{II} may be stated according to the assumption as

$$\Delta P_{II} = \frac{dP}{dm_2} \Delta m_2 \tag{13}$$

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where dP/dm_2 is the slope of the diffuser characteristic. From equations (7), (11), and (12), ΔP_{II} may be evaluated as

$$\Delta P_{II} = \frac{- \frac{m}{\gamma P} \left(\frac{dP}{dm_2}\right) \frac{W_A}{A_1} \frac{d}{dt} \Delta u + \frac{m_x}{a_2 M_2} \left(\frac{dP}{dm_2}\right) \Delta u}{1 - \frac{m}{\gamma P} \left(\frac{dP}{dm_2}\right)} \tag{13a}$$

By substitution of equations (11), (12), and (13a) into equation (10) to eliminate all variables except Δu, a second-order, linear differential equation of constant coefficients for the resonant process in a ram jet without combustion may be obtained:

$$\frac{W_C}{m_x} \frac{W_A}{\gamma P A_1} \frac{d^2}{dt^2} \Delta u - \frac{W_C}{\gamma P a_2 M_2} \left[\frac{dP}{dm_2} - \frac{\gamma - 1}{2} \frac{W_A}{W_C} \left(\frac{m}{m_x}\right) \frac{a_2}{A_1} M_2\right] \frac{d}{dt} \Delta u +$$

$$\frac{1}{a_2 M_2} \left(1 - \frac{\gamma + 1}{2\gamma} \frac{m}{P} \frac{dP}{dm_2}\right) \Delta u = 0 \tag{14}$$

The general form of equation (14) is that of the commonly known free-vibration equation:

$$K_1 \frac{d^2}{dt^2} \Delta u - K_2 \frac{d}{dt} \Delta u + K_3 \Delta u = 0 \tag{14a}$$

(See ref. 4, for example.) The solutions for the amplitude and the frequency, respectively, may be written as

$$\Delta u = B \, e^{\frac{K_2}{2K_1} t} \cos\left[t\sqrt{\frac{K_3}{K_1} - \left(\frac{K_2}{2K_1}\right)^2} + \varphi\right] \tag{14b}$$

and

$$f = \frac{1}{2\pi}\sqrt{\frac{K_3}{K_1} - \left(\frac{K_2}{2K_1}\right)^2} \tag{14c}$$

where B and φ are constants of integration. Inasmuch as the derivation of equation (14) has assumed small amplitudes of oscillation and friction effects have been neglected, equation (14) cannot be used to predict variations in amplitude with time.

Theoretical stability criterion. - According to equation (14), a ram-jet diffuser will deliver air to the combustion chamber without pulsation if the coefficient of $\frac{d}{dt} \Delta u$ is positive. Thus, any pressure disturbance in the system will die exponentially with time. Furthermore, the diffuser will be unstable if the coefficient of $\frac{d}{dt} \Delta u$ is negative and any pressure disturbance in the system will then be amplified exponentially with time. For the special case when the coefficient of $\frac{d}{dt} \Delta u$ equals zero, equation (14) describes a sine-wave oscillation of constant amplitude.

Examination of equation (14) reveals that the coefficient of $\frac{d}{dt} \Delta u$ will be positive or negative accordingly as the term

$\left[\frac{dP}{dm_2} - \frac{\gamma-1}{2}\frac{W_A}{W_C}\left(\frac{m}{m_x}\right)\frac{a_2}{A_1}M_2\right]$ is negative or positive. If $\frac{dP}{dm_2}$ is negative, a stable system results. If the value of dP/dm_2 is positive and larger than the term $\frac{\gamma-1}{2}\frac{W_A}{W_C}\left(\frac{m}{m_x}\right)\frac{a_2}{A_1}M_2$, however, an unstable or pulsating system is predicted.

A plot of a physical interpretation of these criterions is presented in figure 2. The curves of figure 2 are essentially a plot of the term $\left[\frac{dP}{dm_2} - \frac{\gamma-1}{2}\frac{W_A}{W_C}\left(\frac{m}{m_x}\right)\frac{a_2}{A_1}M_2\right]$ of equation (14) but include some additional assumptions not made in deriving equation (14). In arriving at the parameters used to plot the curve of figure 2, it was assumed that the mass of the diffuser air column W_A is equivalently given by $\rho L_D A_1$ where L is the diffuser length from station 1 to 2. The mass of air contained in the plenum chamber W_C was assumed to be given by ρV where V is the sum of the volume between stations 2 and 4 and the residual volume of the diffuser (total diffuser volume less volume of air column $L_D A_1$), which is representative of the portion of the diffuser acting essentially as a storage volume. In addition, the resulting parameters have been nondimensionalized.

In figure 2, a curve of a given value of $\frac{m_0}{m_2}\left(\frac{P_2}{P_0}\right)M_2^2$ is the locus of values of the theoretically maximum positive slope of the diffuser characteristic as a function of a parameter of the ram-jet geometry $\frac{L_D A_1}{V}\left(\frac{A_2}{A_1}\right)^2$ that may be tolerated before resonant instability occurs. For example, for a fixed value of the flow-conditions parameter $\frac{m_0}{m_2}\left(\frac{P_2}{P_0}\right)M_2^2$ and a given diffuser characteristic represented by the slope of the diffuser characteristic, increasing diffuser length or inlet area (for a fixed diffuser-area ratio) or decreasing combustion-chamber volume tends to increase the stability of the ram jet. In a like manner, other ram-jet design criterions affecting stability are readily obtained.

<u>Frequency.</u> - An equation for the pulsation frequency of a ram jet may be obtained from equation (14c) using the additional assumptions employed in the foregoing stability-criterions analysis. Thus,

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$$f = \frac{a_2}{2\pi}\sqrt{\frac{A_1}{L_D V}\left\{1 - \frac{\gamma+1}{2} A_2 \frac{M_2}{a_2} \frac{P_0}{m_0} \frac{d\left(\frac{P_2}{P_0}\right)}{d\left(\frac{m_2}{m_0}\right)} - \frac{A_1 V \left(\frac{P_0}{m_0}\right)^2 \left[\frac{d\left(\frac{P_2}{P_0}\right)}{d\left(\frac{m_2}{m_0}\right)} - \frac{\gamma-1}{2} \frac{L_D}{V} \frac{A_2}{A_1} \frac{m_0}{P_0} M_2 a_2\right]^2}{4 a_2^{\,2} L_D}\right\}} \tag{15}$$

It is of interest to note that for a ram jet having a zero slope characteristic and a closed outlet nozzle (that is, zero mass-flow rate), equation (15) reduces to a form of the Helmholtz resonator frequency equation,

$$f = \frac{a_2}{2\pi}\sqrt{\frac{A_1}{L_D V}} \tag{16}$$

Equations (15) and (16) indicate that pulsation frequency will increase as air temperature and diffuser-inlet area are increased and that frequency will decrease as either diffuser length or combustion-chamber volume is increased. Furthermore, as the slope of the diffuser characteristic increases, the frequency of pulsation will diminish. Thus for diffusers having pressure-recovery curves of varying slope, changes in pulsation frequency with changes in mass-flow ratio may be expected.

An imaginary solution is obtained for the frequency (equation (15)) if very large diffuser characteristic slopes are encountered, In such cases, a hyperbolic solution instead of a sinusoidal solution, as given by equation (14b), results, and theoretical frequency as such holds no real physical significance.

Experimental Verification

Stability criterion. - Experimental data were obtained for a variety of conditions to provide a check of the theory. Employed in the studies were numerous diffuser and ram-jet designs (figs. 3 and 4). The data were obtained at various Mach numbers in several supersonic tunnels and a supersonic free jet. The throttling of the exit jet was fixed for each datum point so that no transient effects associated with changes in throttling were included. Pressure fluctuations in the ram jet were sensed with commercial diaphragm-type pressure pickups, and recordings of these pressures were made with a commercial tape recorder. The pressure-pickup frequency measurements were checked with high-speed movies of the normal-shock oscillations at the diffuser inlets, and excellent agreement was obtained in all cases.

One set of experiments provided data (figs. 5 and 6) showing the effects on diffuser flow pulsations of minor changes in the projection of the diffuser conical spike of a ram jet at zero attack angle and a given free-stream Mach number. The data were obtained in a $M_0 = 1.77$ free jet with a 16-inch ram jet (figs. 3(a) and 4(a)) having a single shock projecting cone with all external compression and a sharp-edged inlet.

A plot of the diffuser pressure recovery as a function of diffuser mass-flow ratio is shown in figure 5. There is reasonable agreement of the theoretical stability criterion with experiment. In all cases where the slope of the diffuser pressure recovery against mass-flow-ratio curve was negative, no detectable oscillation of diffuser-outlet pressures was obtained. At operating conditions where this curve had a positive slope of some magnitude, however, unstable pulsating flow was obtained.

The data of figure 5 are plotted in figure 6 in accordance with the stability criterions shown in figure 2. For each data point, the slope of the diffuser characteristic is plotted as a function of mass-flow ratio and the stability condition is indicated. As in figure 5, a reasonable agreement of theory with experiment is shown.

Another investigation was conducted to determine the effects at zero angle of attack (figs. 7 and 8) of a change in free-stream Mach number (from 1.50 to 2.00) on diffuser flow pulsations for a fixed engine configuration. The study was made in the Lewis 8- by 6-foot supersonic tunnel with a 16-inch ram jet (fig. 4(d)) having a single shock projecting-cone diffuser with both internal and external compression (fig. 3(f)). A rounded-lip diffuser inlet was employed.

As with the data presented in figures 5 and 6, experimental results agree reasonably well with theory. A positive slope on the diffuser characteristic is also necessary for pulsation in this case. At M_0 values of 1.50 and 1.60, no pulsation was observed over the mass-flow range investigated. Pulsation was first observed to occur at M_0 of 1.70, but only over a portion of the diffuser curve in the subcritical flow operating range. Pulsating flow was encountered for all subcritical flow conditions at which data were obtained for M_0 values of 1.90 and 2.00. In no case was pulsation observed to occur when the slope of the diffuser curve was negative.

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In order to determine experimentally what effect, if any, a change in combustion-chamber volume would have on the pulsing characteristics of a ram jet, the combustion-chamber volume of the 16-inch ram jet just discussed (figs. 4(d) and 3(f)) was increased approximately 2.3 times. Figures 9 and 10 present the results of an investigation of this modified ram jet conducted at M_0 values of 1.60, 1.80, and 2.00. No significant changes in the stability characteristics were observed, except that some pulsation did appear over a small range of subcritical mass flow at M_0 of 1.60; pulsation at an M_0 of 1.60 did not occur in the investigation with the smaller combustion-chamber volume. Again reasonable agreement of the theory with experiment was obtained. The significant changes in pulsation frequency that occurred will be subsequently discussed.

Flow-pulsation data (figs. 11 and 12) were also obtained from a number of experiments on 8-inch ram jets (figs. 4(b) and 4(c)), which show the effect of major ram-jet and diffuser design changes on diffuser flow instability. The ram jets were equipped with diffusers having (1) an isentropic compression projecting spike with all external compression and a round-edged inlet (fig. 3(d)), (2) a single-shock projecting cone with all external compression (figs. 3(b) and 3(e)), and (3) a single-shock projecting cone with both internal and external compression and a round-edged inlet (fig. 3(c)). The data were obtained in the Lewis 8- by 6-foot supersonic tunnel and the Lewis 20-inch supersonic tunnel at values of M_0 of 1.79 and 1.99 for zero angle of attack.

In all cases presented in figures 11 and 12, the same criterions already presented, which establish the likely conditions of diffuser flow pulsation, were again observed. The data presented in figures 5 to 12 indicate that the theory reasonably predicts the stability of a ram jet.

Frequency. - Experimental frequency data and the computed frequency curves (using equation (15)) for three ram jets are presented in figures 13 and 14 as a function of mass-flow ratio. The data were obtained at zero angle of attack and cover a range of free-stream Mach number from 1.77 to 2.00. The ram-jet and diffuser configurations are some of those already described and are illustrated in figures 3 and 4.

For the three ram jets studied, the theoretical-frequency curves show good agreement with experimental frequencies both as to magnitude and trend. These data include the effects of changes in diffuser characteristic, mass-flow ratio, and combustion-chamber volume.

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PULSATION WITH COMBUSTION

Theory

A generalized treatment of the resonance characteristics of ram jets with heat addition is very difficult because no single or fixed pattern of heat addition exists. By examination of some special cases, which in some degree approximate the combustion process in ram jets, effects of heat addition on the resonance characteristics may be estimated.

As a theoretical example, a case may be considered where a fuel flowing at a constant rate is burned at constant efficiency. The fuel may be assumed to burn instantaneously and uniformly at the combustion-chamber entrance and temperature changes at the entrance are transmitted throughout the combustion chamber in a time that is short compared with the period of oscillation. Thus a uniform temperature T_4 is assumed to exist throughout the combustion chamber. The temperature is also considered to increase at a uniform rate with fuel-air ratio.

Before continuing the discussion of the effects of heat addition on the resonance properties of a ram jet, the reasonableness of the temperature time-lag effects should be briefly analyzed. If the time lag of temperature, due to fluid transport from station 2 to station 4, is approximately given by

$$t \approx \frac{L_C}{u_3} \approx \frac{L_C}{\sqrt{\gamma_2 R T_2 \tau}\, M_2}$$

then for low values of M_2 the assumption of uniform temperature throughout the combustion chamber is a poor one for quantitative analyses. If the value of M_2 is relatively high (say, $M_2 = 0.25$ and $\tau = 4.0$), the rate of fluid transport is of the order of the rate of sound propagation in cold air; the assumption of constant temperature throughout the combustion chamber would then be as valid as the constant-pressure assumption in the case without combustion. Under this condition, however, the velocity of the fluid in the combustion chamber approaches the velocity of sound. The validity of the assumption of constant pressure throughout the combustion chamber and the neglect of inertia forces are questionable. The analysis would again be expected to give only qualitative trends.

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Application of the foregoing assumptions regarding the heat-addition process leaves equation (7) unchanged for the mass-flow rate past station 2, but forces a modification of equation (8) for the mass-flow rate past station 4 and equation (9) for the rate of mass accumulation in the ram jet. The change in mass-flow rate at station 4 arising from a mass-flow perturbation is given by

$$\Delta m_4 = m\left(\frac{\Delta P_4}{P_4} - \frac{1}{2}\frac{\Delta T_4}{T_4}\right) \tag{17}$$

The rate of mass accumulation in the ram jet between stations 2 to 4 is given by

$$\frac{d}{dt}\Delta W_C = \frac{d}{dt}\Delta W_{SD} + \frac{d}{dt}\Delta W_{SC} \tag{18}$$

where $\frac{d}{dt}\Delta W_{SD}$ is the rate of mass accumulation in the diffuser between station 2 and the flame holder, and $\frac{d}{dt}\Delta W_{SC}$ is the rate of mass accumulation in the combustion chamber at temperature T_4 between the flame holder and station 4. Expanding equation (18) gives

$$\frac{d}{dt}\Delta W_C = W_{SD}\left(\frac{d}{dt}\frac{\Delta P_2}{P_2} - \frac{d}{dt}\frac{\Delta T_2}{T_2}\right) + W_{SC}\left(\frac{d}{dt}\frac{\Delta P_4}{P_4} - \frac{d}{dt}\frac{\Delta T_4}{T_4}\right) \tag{19}$$

The temperature change ΔT_4 in equations (17) and (19) is made up of two terms: one depending upon the adiabatic compression value (equation (6)), and the second depending on the rate of heat addition due to combustion. Thus,

$$\Delta T_4 = \Delta T_{4,c} + \Delta T_{4,b} \tag{20}$$

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In line with the assumptions concerning the combustion process, the temperature change at station 2 due to combustion has a value given by

$$m_2\, c_p \left(T_4 - T_2\right) = m_f H\, \eta_b \tag{21}$$

and for a constant value of fuel flow and combustion efficiency,

$$\Delta m_2 \left(T_4 - T_2\right) + m_2\, \Delta T_{4,b} = 0$$

$$\frac{\Delta T_{4,b}}{T_4} = -\left(1 - \frac{1}{\tau}\right)\frac{\Delta m_2}{m} \tag{22}$$

where τ is the stagnation temperature ratio.

Similarly, the pressure change ΔP_4 in equations (17) and (19) is made up of the pressure increments ΔP_I and ΔP_{II} (previously defined) and the change in pressure across the combustion chamber due to the change in temperature arising from the addition of heat. Thus,

$$\Delta P_4 = \Delta P_I + \Delta P_{II} + \Delta P_b \tag{23}$$

In evaluating the pressure increment ΔP_b, the drop in pressure across the combustion chamber due to heat addition is approximately given by (ref. 7)

$$\frac{P_2 - P_4}{P_2} \approx -\frac{\gamma_2 M_2{}^2}{2}\left(\frac{T_4}{T_2} - 1\right)$$

or differentiating,

$$\frac{\Delta P_b}{P_2} = \frac{\gamma_2 M_2{}^2}{2}(\tau - 1)\left[\frac{\tau}{\tau - 1}\left(\frac{\Delta T_4}{T_4} - \frac{\Delta T_2}{T_2}\right) + 2\,\frac{\Delta M_2}{M_2} + \frac{\Delta P_2}{P_2}\right] \tag{24}$$

Application of the approximate relation

$$M_2{}^2 \frac{T_4}{T_2} = \text{constant}$$

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presented in reference 7 for choked steady-flow ram jets allows the quantity $\Delta M_2/M_2$ to be evaluated. From equations (20), (22), and (6),

$$\frac{\Delta T_4}{T_4} = -\frac{(\tau-1)}{\tau}\frac{\Delta m_2}{m} + \frac{\gamma_4-1}{\gamma_4}\left(\frac{\Delta P_2}{P_2} + \frac{\Delta P_b}{P_2}\right)$$

By combination with equations (6) and (24), the pressure drop across the combustion zone becomes

$$\frac{\Delta P_b}{P_2} = \frac{\frac{\gamma_2 M_2{}^2}{2}(\tau-1)}{1 - \frac{\gamma_2(\gamma_4-1)M_2{}^2}{2\gamma_4}}\left[\frac{\Delta P_2}{P_2}\left(1 - \frac{\gamma_2-\gamma_4}{\gamma_2\gamma_4(\tau-1)}\right) - \frac{1}{\tau}\frac{\Delta m_2}{m}\right] \tag{24b}$$

From a simultaneous solution of equations (1), (6), (7), (17), and (19) using the proper values of ΔP and ΔT given in the foregoing discussion, a second-order linear differential equation for the resonant process in a ram jet with combustion may be obtained. Thus for ram jets having a combustion process such that a rise in combustion temperature is obtained from an increase in fuel-air ratio, the resonance equation is

$$\frac{W_A}{P_2 A_1}\left(B + \frac{D}{\gamma_2}\right)\frac{d^2\Delta u}{dt^2} -$$

$$\left[\frac{m_x}{a_2 M_2}\left(\frac{B}{P_2}\frac{dP}{dm_2} + \frac{D}{m}\right) + \frac{m}{\gamma_2 P_2}\frac{W_A}{A_1} - \frac{m}{P_2}\frac{W_A}{A_1}\left(E + \frac{F}{\gamma_2}\right)\right]\frac{d}{dt}\Delta u +$$

$$\frac{m_x}{a_2 M_2}\left[1 - m\left(\frac{E}{P_2}\frac{dP}{dm_2} + \frac{F}{m}\right)\right]\Delta u = 0 \tag{25}$$

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where

$$B = \left[\frac{W_D}{\gamma_2} + W_C + W_C \frac{\frac{\gamma_2 M_2{}^2}{2}(\tau-1)}{1 - \frac{\gamma_2(\gamma_4-1)}{2\gamma_4}M_2{}^2}\left(1 - \frac{\gamma_2-1}{\gamma_2(\tau-1)} + \frac{\gamma_4-1}{\gamma_4(\tau-1)}\right) - (\tau-1)\ W_C \left(\frac{1 - \frac{\gamma_2-1}{\gamma_2(\tau-1)} + \frac{\gamma_4-1}{\gamma_4(\tau-1)}}{1 - \frac{\gamma_2(\gamma_4-1)M_2{}^2}{2\gamma_4}} + \frac{\gamma_2-1}{\gamma_2(l-1)} - 1\right)\right]$$

$$D = \frac{W_C}{1 - \frac{\gamma_2(\gamma_4-1)M_2{}^2}{2\gamma_4}}\left(\frac{\tau-1}{\tau} - \frac{\gamma_2 M_2{}^2(\tau-1)}{2\tau}\right)$$

$$E = \left\{1 + \left[\frac{\frac{\gamma_2 M_2{}^2}{2}(\tau-1)}{1 - \frac{\gamma_2(\gamma_4-1)M_2{}^2}{2\gamma_4}} - \frac{\tau-1}{2\left(1 - \frac{\gamma_2(\gamma_4-1)M_2{}^2}{2\gamma_4}\right)}\right]\left[1 - \frac{\gamma_2-1}{\gamma_2(\tau-1)} + \frac{\gamma_4+1}{\gamma_4(\tau-1)}\right] + \frac{\tau-1}{2}\left[1 - \frac{\gamma_2-1}{\gamma_2(\tau-1)}\right]\right\}$$

and

$$F = \frac{(\tau-1)(1-\gamma_2 M_2{}^2)}{2\left[1 - \frac{\gamma_2(\gamma_4-1)}{2\gamma_4}M_2{}^2\right]\tau}$$

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The solution of equation (25) is represented by equations (14b) and (14c).

Theoretical stability criterion. - As with equation (14), equation (25) offers certain criterions that establish the resonance characteristics of a ram jet with combustion. Again, a ram-jet diffuser will be stable or unstable accordingly as the coefficient of $\frac{d}{dt} \Delta u$ is positive or negative. The stability criterions are therefore given by equating the coefficient to zero. For illustrative purposes, the quantities $\frac{dP}{dm_2}$, M_2, and W_A will be evaluated as in the case without heat addition. In addition, the values of $\gamma_4 = \gamma_2 - 0.03(\tau-1)$ and $\gamma_2 = 1.4$ have been assumed.

Equating the coefficient of $\frac{d}{dt} \Delta u$ to zero leads to the relation

$$\frac{d\left(\frac{P_2}{P_0}\right)}{d\left(\frac{m_2}{m_0}\right)} \frac{m_2}{m_0} \frac{P_0}{P_2} \left(\frac{V_D}{V_C} + Q\right) + R + S\left[\frac{L_D A_1}{V_C} \left(\frac{A_2}{A_1}\right)^2\right] = 0$$

where Q, R, and S are functions of only M_2 and τ and are given as

$$Q = \frac{\gamma_2}{W_C \tau} \left(B - \frac{W_D}{\gamma_2}\right)$$

$$R = \frac{\gamma_2}{W_C \tau} D$$

$$S = \frac{\gamma_2 {M_2}^2}{\left(1 + \frac{\gamma_2 - 1}{2} {M_2}^2\right)^{\frac{\gamma_2}{\gamma_2 - 1}}} \left[1 - (\gamma_2 E + F)\right]$$

The quantities Q, R, and S have been graphed in figure 15 for values of M_2 from 0 to 1.0 and values of $\tau\,(T_4/T_2)$ from 1 to 10.

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As for the case without combustion, the physical quantities comprising the coefficient of $\frac{d}{dt}\Delta u$ are combined in parametric form to show the effect of engine geometry and heat addition on the stability characteristics of any given diffuser. Plotted in figures figures 16(a) and 16(b) are these stability criterions for a fixed value of M_2 (variable engine-outlet area) and for a fixed value of $M_2\sqrt{\tau}$ (fixed engine-outlet area), respectively.

As for the case with no heat addition, a curve of a constant engine-geometry parameter is the locus of the maximum values of the theoretical slope function at any mean total-temperature ratio across the engine that may be tolerated before resonant instability occurs. Thus ram jets with small values of the engine-geometry parameter tend to become resonantly less stable with increased heat addition; whereas ram jets with very large values of the engine-geometry parameter tend to improve their resonant stability properties with increased heat addition. For example, shortening a ram-jet combustion chamber tends to improve the resonant stability properties. The same improvement in resonance stability might also be achieved by lengthening the diffuser. Most currently used ram jets have very low values of the geometry parameter.

Frequency. - Estimation of pulsation frequency is obtained from equation (14c). As in the case without heat addition, pulsation amplitude cannot be determined from equation (25).

Experimental Verification

Stability criterion. - Because of lack of experimental data, an exhaustive quantitative check of the theory has not as yet been made; however, some experimental data were available for an approximate qualitative check of the theoretical trends. Combustion experiments were conducted in which diffuser-pulsation data were obtained with a 16-inch-diameter ram jet in a supersonic free jet and employing a burner using two different fuels, gasoline and a blend of 75-percent kerosene and 25-percent propylene oxide. Data were obtained at M_0 values of 1.58 and 1.77. The ram jet and burner are shown in figures 4(a) and 17, respectively. The burner employed a commercial spray-nozzle system injecting fuel in an upstream direction 18 inches ahead of the flame holder. The flame holder was mounted at the outlet of a vortex-type pilot burner forming the end of the ram-jet diffuser center body. The same pressure pickup and recording instruments were used for pressure-fluxtuation measurement as previously described for the case without combustion.

The results of the experiments using gasoline are presented in figures 18 to 20 where plots of diffuser pressure recovery as a function of mass-flow ratio (fig. 18), the slopes of the pressure-recovery curve as a function of mass-flow ratio (fig. 19), and traces of the pressure fluctuations for representative data points (fig. 20) are shown. The data points of figure 18 are noted with numbers that correspond to those numbers in figure 20 to show corresponding pressure traces. A comparison of the data obtained with and without combustion show that in both cases for supercritical operation of the diffuser, pulsation-free flow was obtained in the ram jet. For the case with heat addition, pulsating flow was obtained over the entire subcritical operating range where pulsation-free flow had been obtained with no heat addition. The design of this ram jet was such that an increase in heat addition markedly decreased its theoretical resonance stability properties in the subcritical operating range. (See fig. 19.) All the data of figure 18 indicating unstable operation are theoretically predicted to be unstable by virtue of the resonance properties of the engine, as shown in figure 19.

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Flow-pulsation data obtained with the same engine and burner configuration using the kerosene - propylene oxide fuel blend are presented in figures 21 to 23. The change in fuel caused a pressure pulsation presumed to arise from the combustion process that persisted over the entire subcritical and supercritical mass-flow range. The influence of diffuser flow pulsations evidenced by the larger amplitudes can be noted over the entire range of subcritical flows. (See fig. 23.) In this case, resonances associated with the combustion process have occurred that are not predicted by the simplified theory included herein.

Frequency. - From the pressure fluctuation traces of figures 20 and 23, it can be seen that a wide range of frequencies will occur with combustion in the ram jet. Rough estimates of the main frequency components were obtained from these pressure-time traces. The lowest value of the measured frequency was about twice the theoretical fundamental frequency (approximately 10 cps) computed from equation (14c).

This trend of higher values for the experimental frequency could have been anticipated. In the theoretical model, without combustion, the inertia terms arose from those portions of the flow where the velocity was highest (that is, in the diffuser). In the case with combustion, high gas velocities also occur downstream of the flame holder; the gas in the combustion chamber would then be expected to exert large inertia effects that were neglected in the theory. The combustion chamber then serves more as an oscillating piston and less as a storage volume. As a rough estimate, the corresponding frequency should be increased in the proportion $\sqrt{\frac{V_D + V_C}{V_D}} \approx 3$.

CONTROLLING FLOW PULSATIONS

Consideration of the criterions presented herein yields a number of feasible schemes for preventing or avoiding resonantly amplified flow pulsations. Presented in figure 24 is a graphic picture of some ram-jet design trends that would improve the resonance stability of a ram jet having the previously assumed combustion characteristics employed in obtaining the theoretical curves of figure 16. (Variable engine-outlet area to yield constant average M_2 with changing values of τ.)

Configuration 1 in figure 24 is typical of present-day ram jets and shows a decrease in resonance stability with heat addition to a temperature ratio of about 3.0. Further increases in heat addition show an increase in resonance stability, but the degree of stability that was obtained without heat addition is not realized until temperature ratios greater than 8.0 are reached. Configuration 2 shows that some improvement in resonance stability is obtained by decreasing the combustion-chamber volume (in this case, halving the combustion-chamber length). The resonance stability of the ram jet is still less with heat addition, however, than with no heat addition to a temperature ratio of 4.5. If the combustion chamber of configuration 2 represents a practical limit for obtaining reasonable combustion efficiencies, further improvements may be obtained by increasing the diffuser length. This increase is made for configuration 3. For configuration 3, a marked improvement in resonance stability occurs with increased heat addition. Configuration 4 is an example of the extremes a ram-jet design would have to approach in realizing further improvements in resonance stability properties.

Only trends are represented by figure 24 and absolute quantitative values may not be correct. This condition holds especially for extreme cases such as configuration 4, for it would not be expected to properly satisfy basic assumptions made in the analysis. In addition, the extreme ram-jet designs indicated may not be practical engine configurations when other important factors of design are considered. Also, as previously noted, if a combustion or heat-addition process that yielded a decrease in combustion-chamber temperature with increased fuel-air ratio (for example, rich-mixture operation) had been assumed, the trends shown would be reversed. 2147

The resonance properties of a ram jet are also affected by the diffuser design. A diffuser characteristic can be appreciably altered by changes in the contour of the projecting spike and inlet lip (refs. 8 to 10) by changes in the projection of the spike ahead of the inlet lip or by boundary-layer control on the spike.

Under certain conditions of flight, operation of the diffuser at mass flows where pulsations would be encountered as indicated by the point A on figure 25(a) may be unavoidable. In such a case, it is possible to operate the diffuser at the mass-flow rate B and bypass the mass-flow difference B - A to the atmosphere through a combustion-chamber cooling passage or an air-turbine drive for engine accessories. Of course, the amount of permissible bypass air might be restricted because of considerations other than the internal flow.

Still another possible method of pulsation control is to throttle with the diffuser-inlet lip, as indicated in figure 25(b). A series of the throttled-diffuser curves are obtained with different settings of the diffuser-inlet area. Thus operation at reduced mass flows and high diffuser pressure recoveries without pulsation are attainable. A serious disadvantage of this throttling method lies in possible increased external aerodynamic drag at inlet-lip settings other than the design point.

A diffuser pulsation can likewise be canceled with another pulsation of equal magnitude and frequency exactly 180° out of phase. Two possible controlled-pulsation sources are the combustion process and the nozzle-outlet area. By alternately increasing and decreasing τ or decreasing and increasing nozzle-outlet area, the combustion-chamber-inlet pressure can be alternately increased and decreased. Such a controlled pressure pulsation can be adjusted so as to eliminate or minimize any diffuser pulsation. A pressure-sensing mechanism may be devised to obtain a controlled oscillation of engine fuel flow, if τ is to be varied, or to obtain a controlled oscillation of a nozzle-outlet flapper valve or spoiler, if nozzle-outlet area is to be varied. Because of the inherent inertia in such a system, these schemes may be limited to the control of only the relatively low frequency pulsations.

Another method of damping pressure oscillation is accomplished by the addition of a resonator to the primary system. In the case of

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an ordinary pipe with standing waves, suppression is accomplished by adding a branch pipe having a natural frequency of that of the primary pipe. (See fig. 25(c).) It is conceivable that employment of a properly tuned resonator attached to a ram jet could successfully damp out or minimize diffuser flow pulsation of a limited frequency range. The main disadvantage of this system as applied to a flight engine may be that an excessively large damping-resonator volume would be required for effective damping.

Diffuser air-column pulsations may also be minimized by increasing the resistance to pulsation in the diffuser. This minimization might be accomplished, for example, by the addition of a series of screens in the diffuser or by increasing the aerodynamic drag of the flame holder. The desirability of this method of damping is governed, of course, by the magnitude of pressure loss sustained over the required number of screens or other damping resistances for effective damping.

SUMMARY OF RESULTS

From a theoretical and experimental study of ram-jet flow pulsations, the following results were obtained:

1. Application of a Helmholtz resonator concept to the ram-jet flow pulsation phenomenon yielded criterions for determining the resonance stability of ram jets. Briefly, the theory indicated that for the case without combustion, any flow disturbance will be amplified if the curve of diffuser pressure recovery as a function of engine mass flow has a positive slope of some magnitude. At operating conditions where the slope of this curve was less than this critical value, the ram jet was resonantly stable. For the case with combustion in the ram jet, the rate of heat addition has an important effect in that the ram-jet resonance properties are markedly and complexly altered.

2. For the case without combustion, the theoretical resonance criterions were found experimentally to reasonably predict the occurrence of flow pulsations.

3. For the case with combustion, it was found experimentally for one engine configuration using two fuels that flow pulsations were obtained at flow conditions for which pulsation-free flow was obtained without combustion. The occurrence of these pulsations with heat addition was theoretically predicted by use of the resonance properties of the engine.

4. Without combustion in the ram jet, the theoretical frequency checked the experimental frequency reasonably well both as to magnitude and trend. In no case with combustion was the theoretical frequency observed; the lowest value of the measured frequency was approximately twice the theoretical fundamental frequency. 2147

CONCLUDING REMARKS

The results of this study offer considerable evidence that ram-jet diffuser flow pulsations, commonly referred to as a "buzz" phenomenon, are governed by acoustical resonance laws. It can be concluded that the acoustical resonance properties of ram jets are an important factor in establishing the frequency of diffuser flow pulsations. Also, evidence exists suggesting that the amplitude of a flow pulsation is in some measure affected by the resonance properties of the engine. In addition, significant ram-jet design factors that may be important in successfully eliminating or controlling ram-jet flow instability are suggested by the resonance theory.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 14, 1951.

REFERENCES

1. Connors, James F.: Effect of Ram-Jet Pressure Pulsations on Supersonic-Diffuser Performance. NACA RM E50H22, 1950.

2. Ferri, Antonio, and Nucci, Louis M.: The Origin of Aerodynamic Instability of Supersonic Inlets at Subcritical Conditions. NACA RM L50K30, 1951.

3. Fenn, J. B., Forney, H. B., and Garmon, R. C.: Burners for Supersonic Ram-Jets. Ind. and Eng. Chem., vol. 43, no. 7, July 1951, pp. 1663-1671.

4. Den Hartog, J. P.: Mechanical Vibrations. Second ed., McGraw-Hill Book Co., Inc., 1940, p. 332.

5. Heath, W. R., and Elliot, W. R.: Control and Prediction of Pulsation Frequency in a Duct System. Jour. Appl. Mech., vol. 13, no. 4, Dec. 1946, pp. A291-A293.

6. Pearce, R. B.: Causes and Control of Powerplant Surge. Aviation Week, vol. 52, no. 3, Jan. 16, 1950, pp. 21-25.

7. Perchonok, Eugene, Sterbentz, William H., and Moore, Stanley H.: Indirect Methods for Obtaining Ram-Jet Exhaust-Gas Temperature Applied to Fuel-Metering Control. NACA RM E7H27, 1948.

8. Moeckel, W. E., Connors, J. F., and Schroeder, A. H.: Investigation of Shock Diffusers at Mach Number 1.85. I - Projecting Single-Shock Cones. NACA RM E6K27, 1947.

9. Moeckel, W. E., Connors, J. F., and Schroeder, A. H.: Investigation of Shock Diffusers at Mach Number 1.85. II - Projecting Double-Shock Cones. NACA RM E6L13, 1947.

10. Moeckel, W. E., and Connors, J. F.: Investigation of Shock Diffusers at Mach Number 1.85. III - Multiple-Shock and Curved-Contour Projecting Cones. NACA RM E7F13, 1947.

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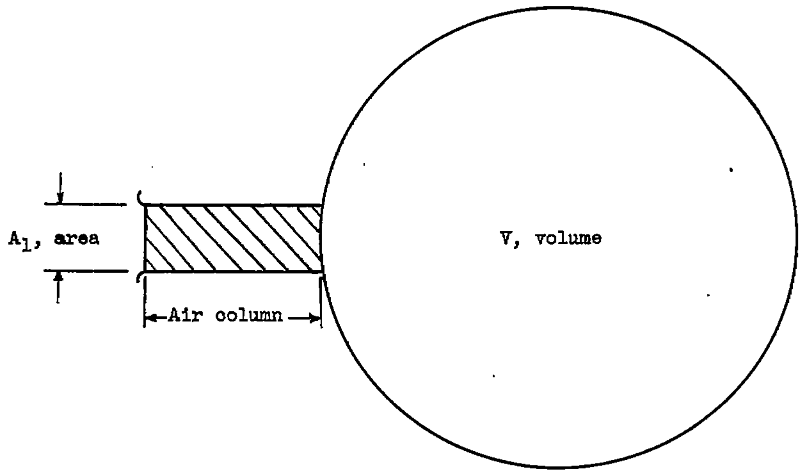
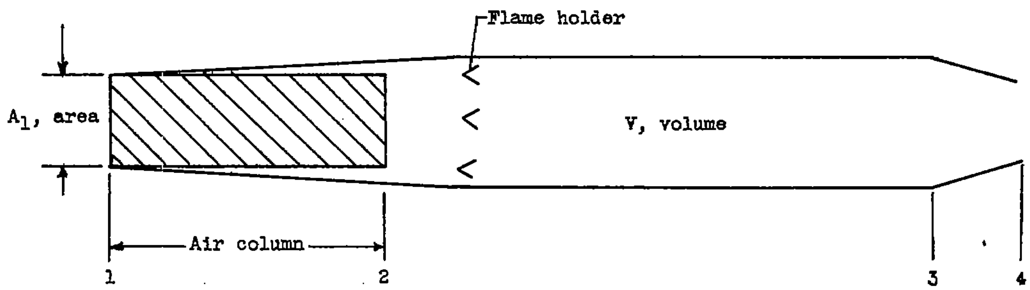
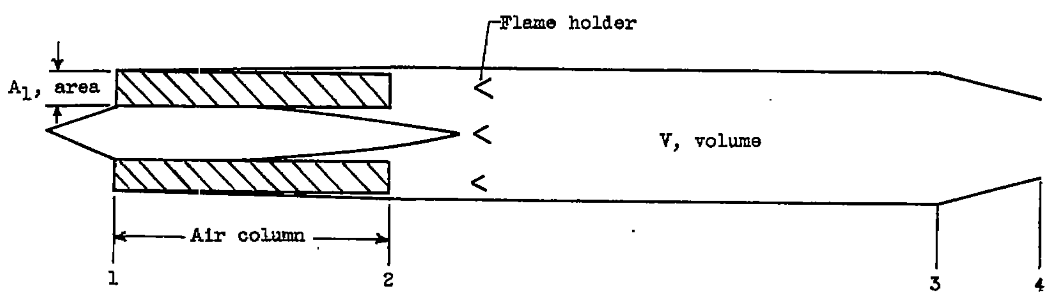


(a) Helmholtz resonator.



(b) Ram jet with diffuser containing no center body.



(c) Ram jet with diffuser containing center body.

Figure 1. - Schematic diagrams of Helmholtz resonator and ram jets showing piston-like air columns.

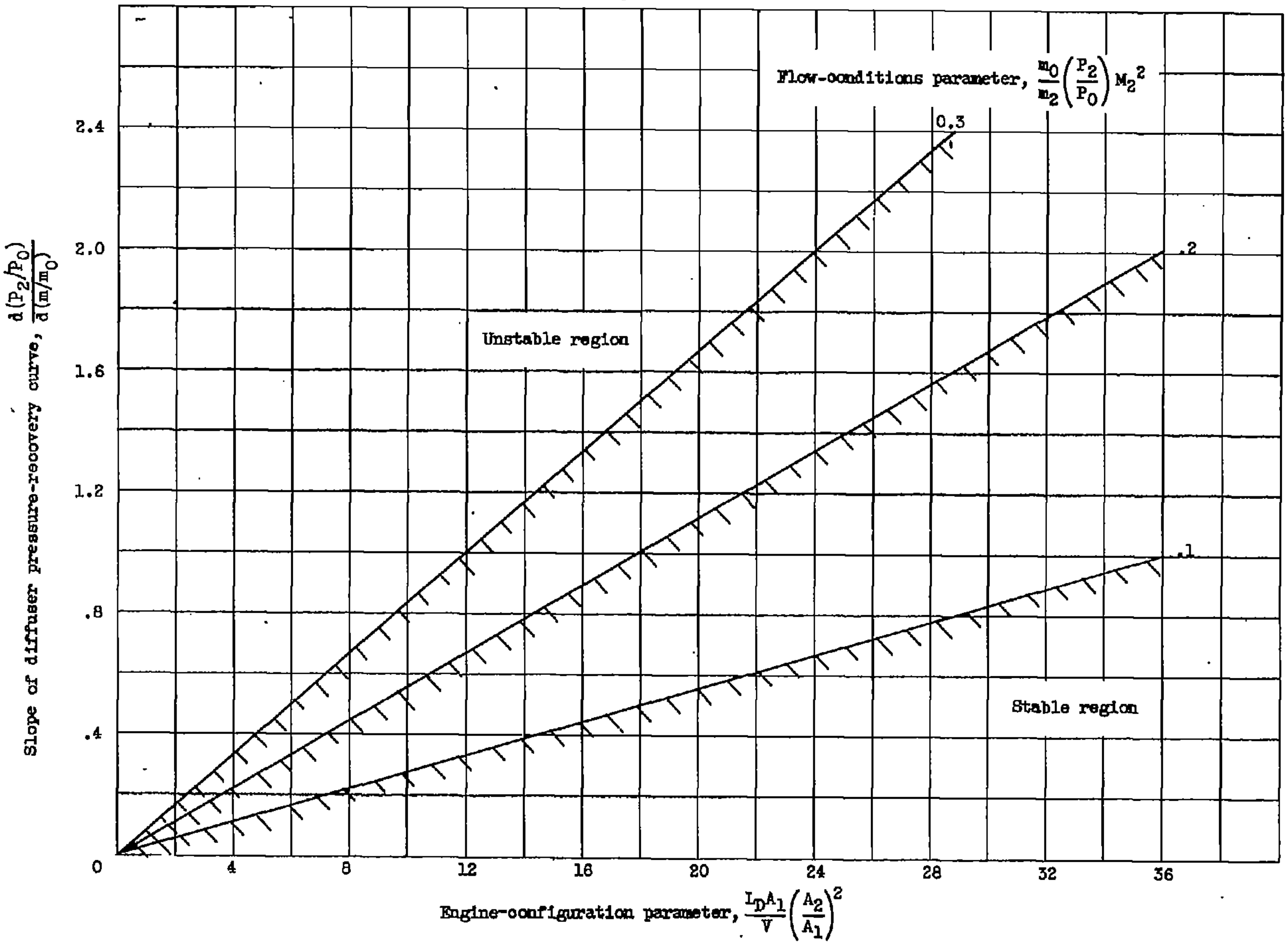
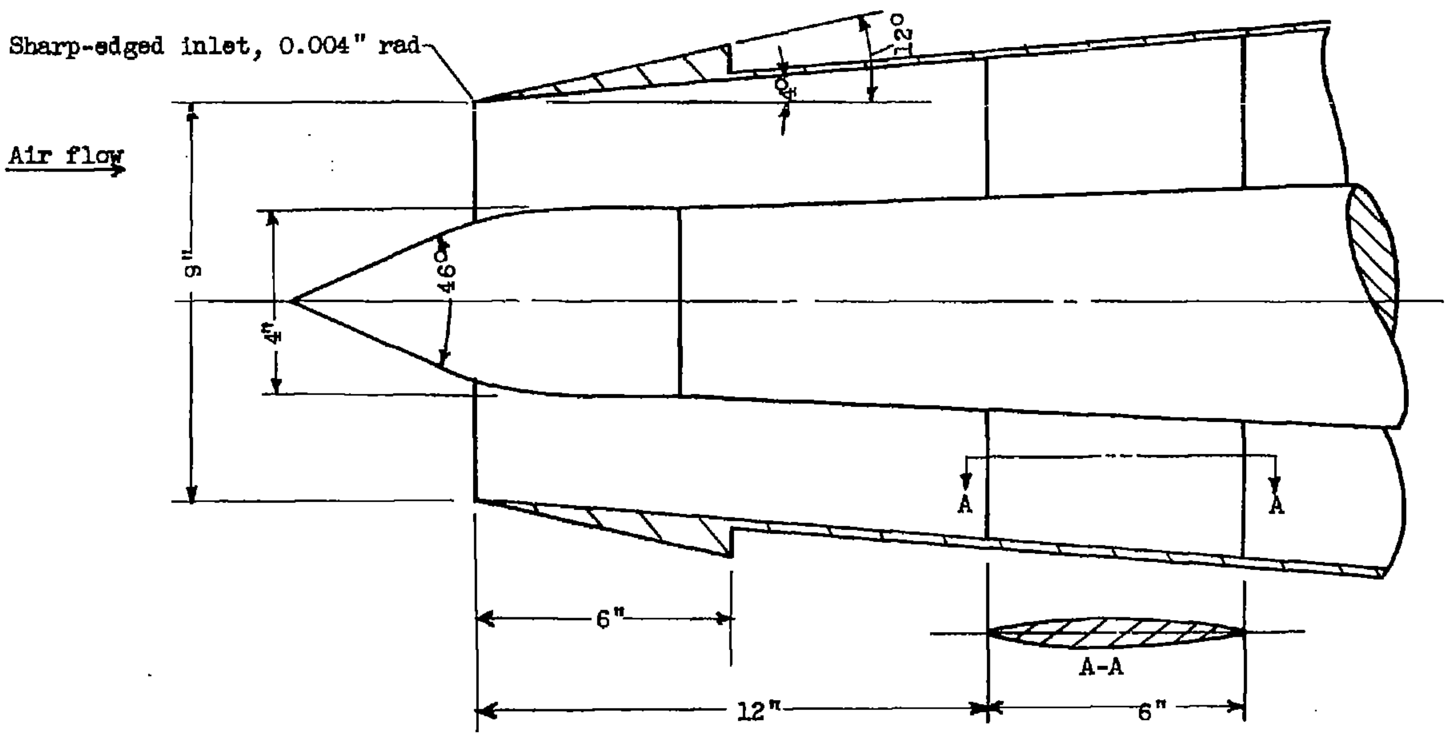
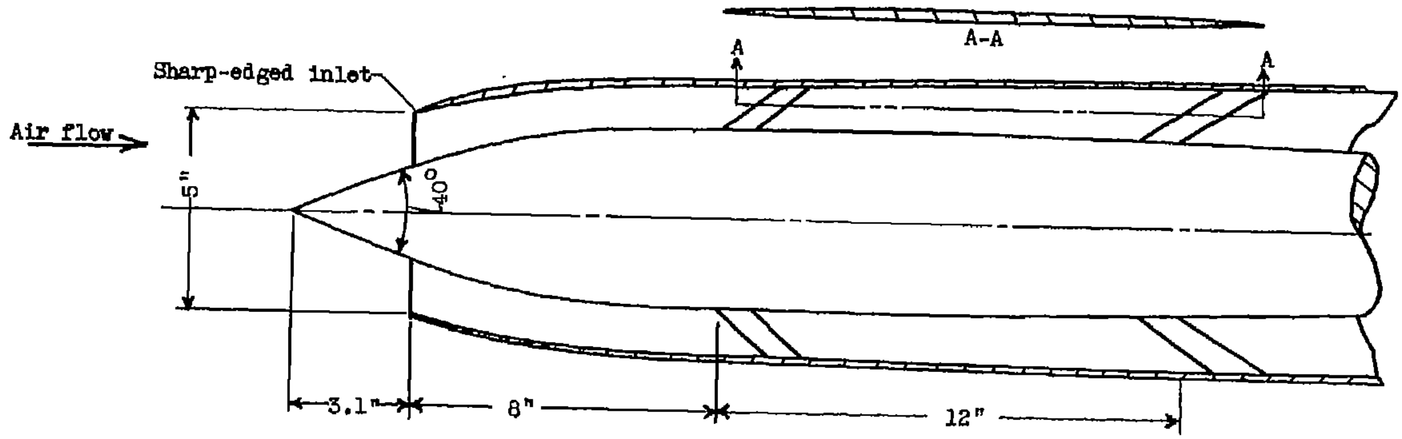


Figure 2. - Theoretical stability criterions without heat addition; $\gamma_2 = 1.4$.

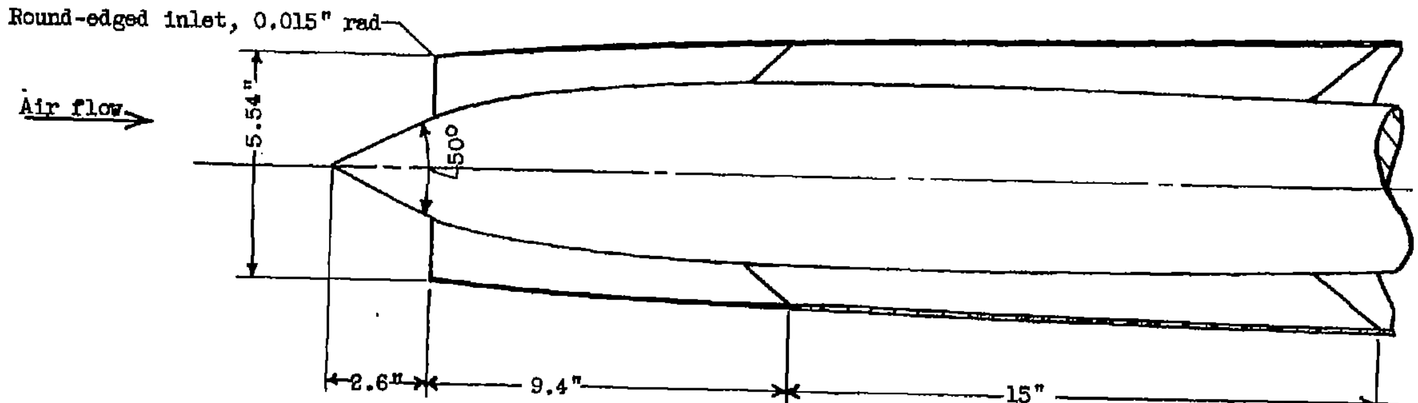


(a) Diffuser employed on 16-inch ram jet studied in supersonic free jet. All external supersonic compression.

Figure 3. - Schematic diagrams of ram-jet diffusers investigated for flow pulsations.

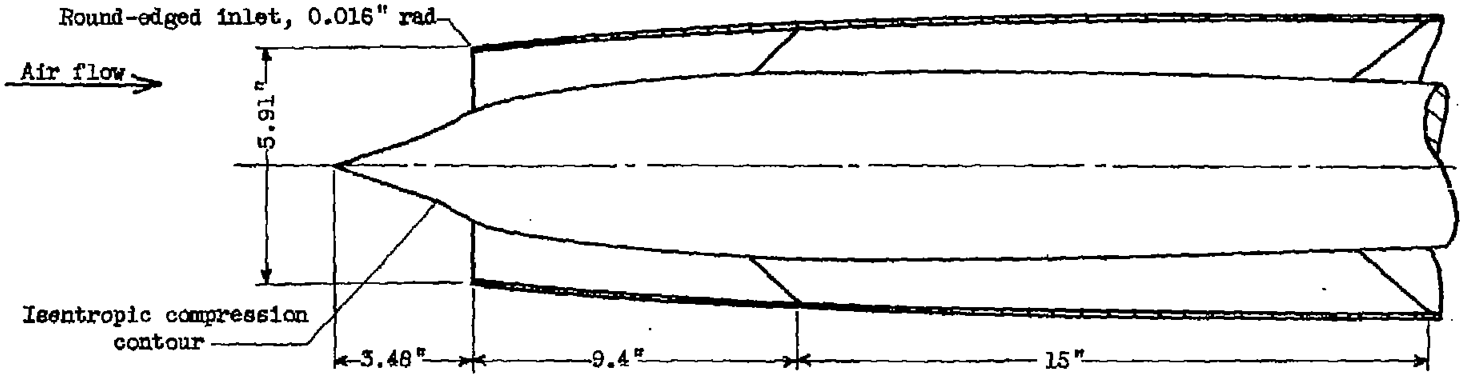


(b) Diffuser employed on 8-inch ram jet studied in 20-inch supersonic tunnel. All external supersonic compression.

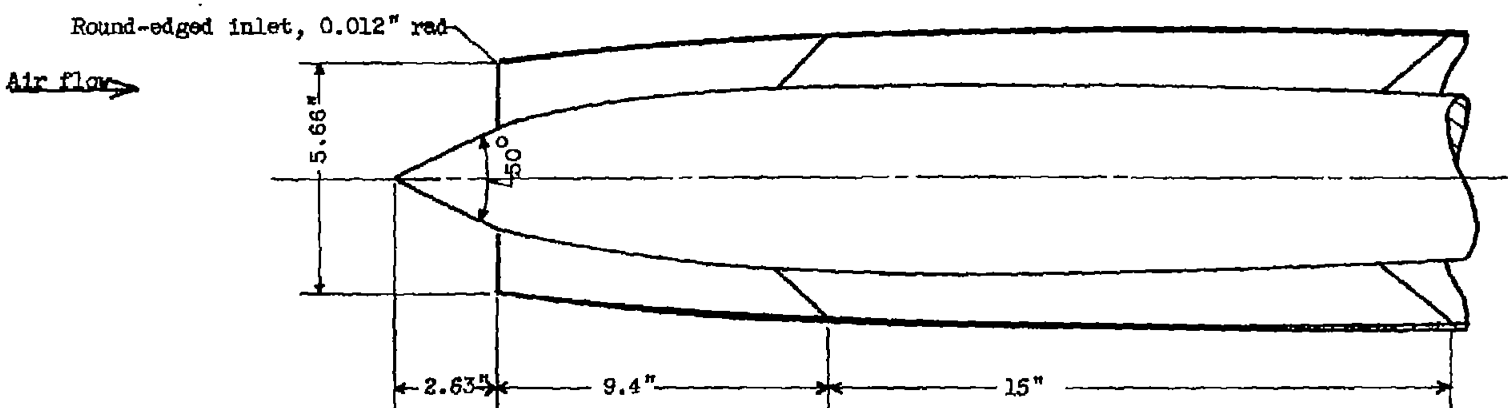


(c) Diffuser employed on 8-inch ram jet studied in 8- by 6-foot supersonic tunnel. External and internal supersonic compression.

Figure 3. - Continued. Schematic diagrams of ram-jet diffusers investigated for flow pulsations.

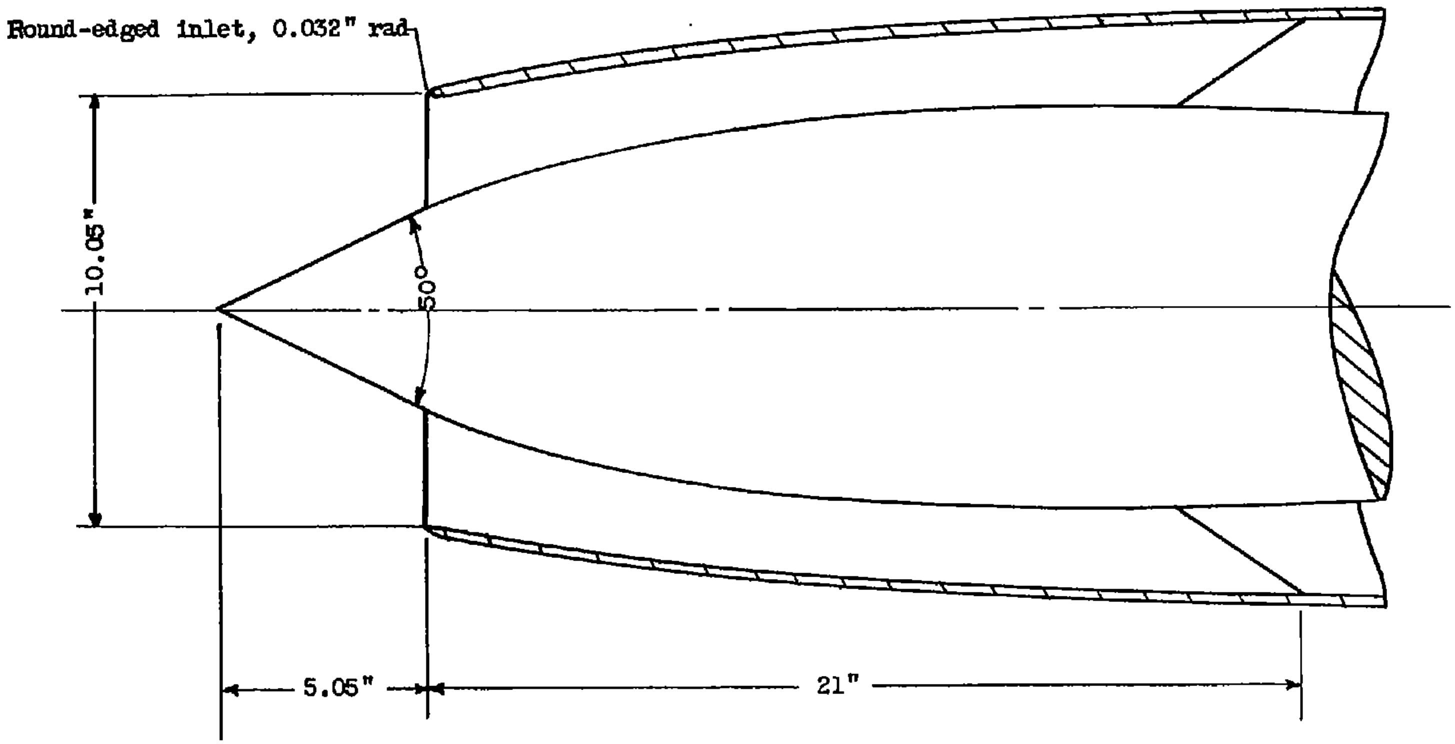


(d) Diffuser employed on 8-inch ram jet studied in 8- by 6-foot supersonic tunnel. Isentropic compression spike.



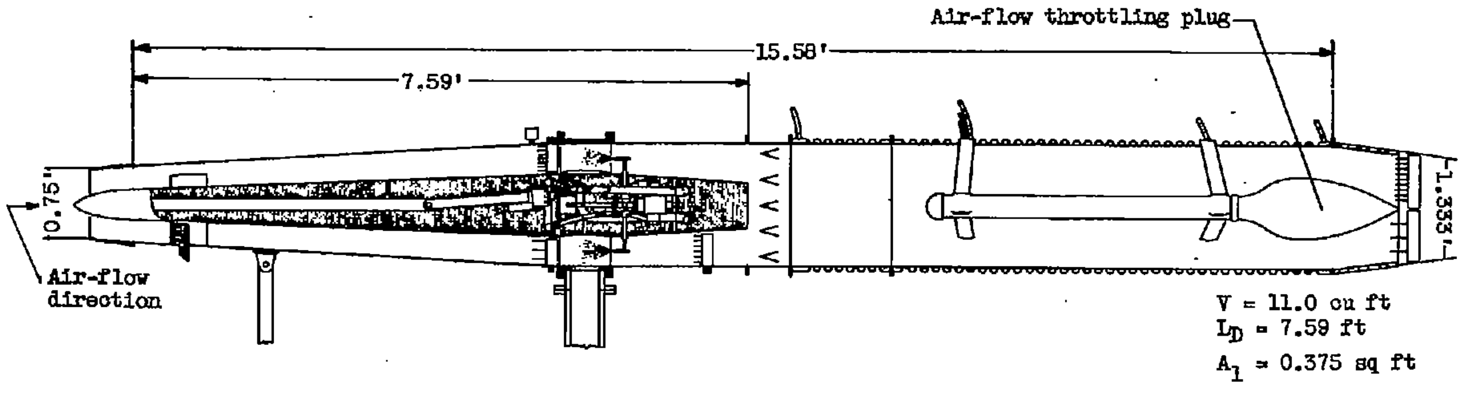
(e) Diffuser employed on 8-inch ram jet studied in 8- by 6-foot supersonic tunnel. All external supersonic compression.

Figure 3. - Continued. Schematic diagrams of ram-jet diffusers investigated for flow pulsations.

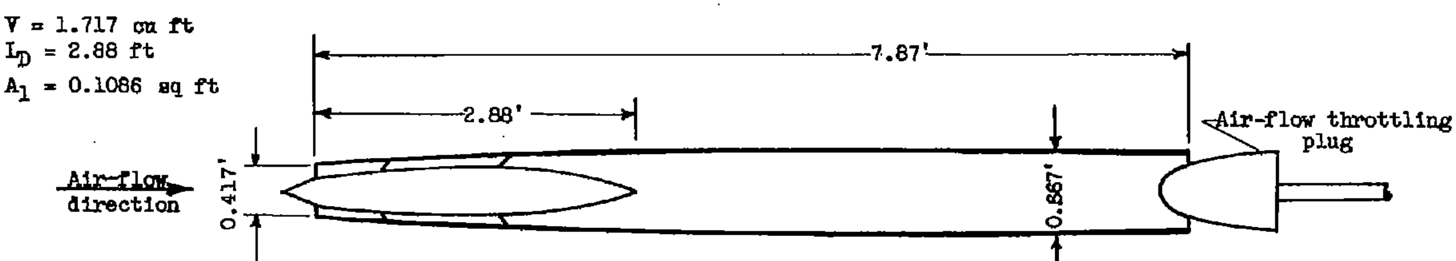


(f) Diffuser employed on 16-inch ram jet studied in 8- by 6-foot supersonic tunnel. External and internal supersonic compression.

Figure 3. - Concluded. Schematic diagrams of ram-jet diffusers investigated for flow pulsations.

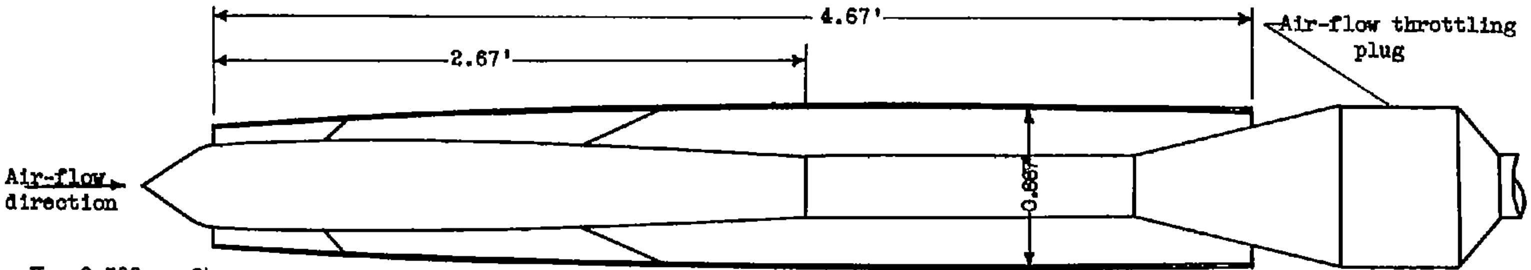


(a) 16-inch ram-jet engine (diffuser illustrated in fig. 3(a)) employed in free-jet experiments.



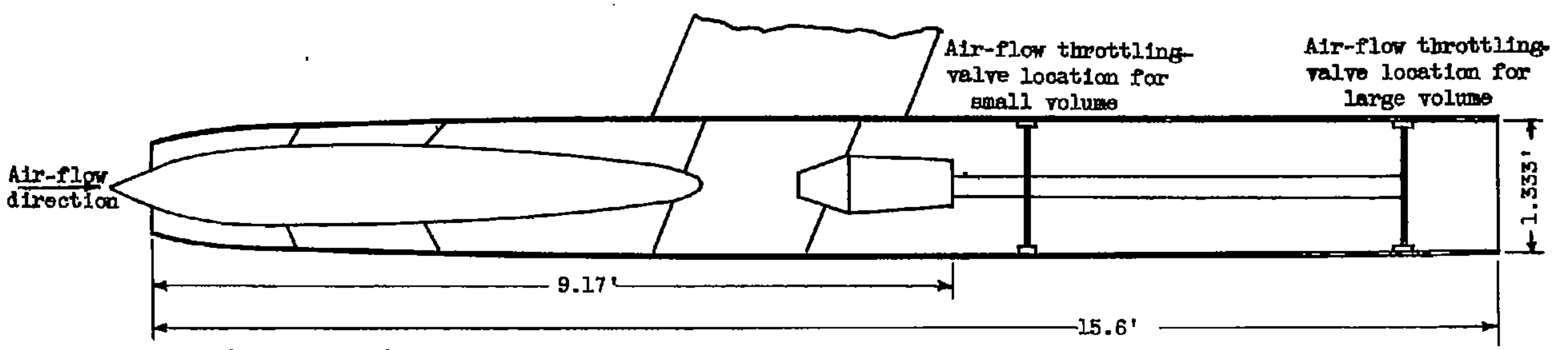
(b) 8-inch ram-jet engine (diffuser illustrated in fig. 3(b)) employed in 20-inch supersonic tunnel experiments.

Figure 4. - Schematic diagrams of ram-jet configurations used in diffuser investigations.



V = 0.580 cu ft
L_D = 2.67 ft

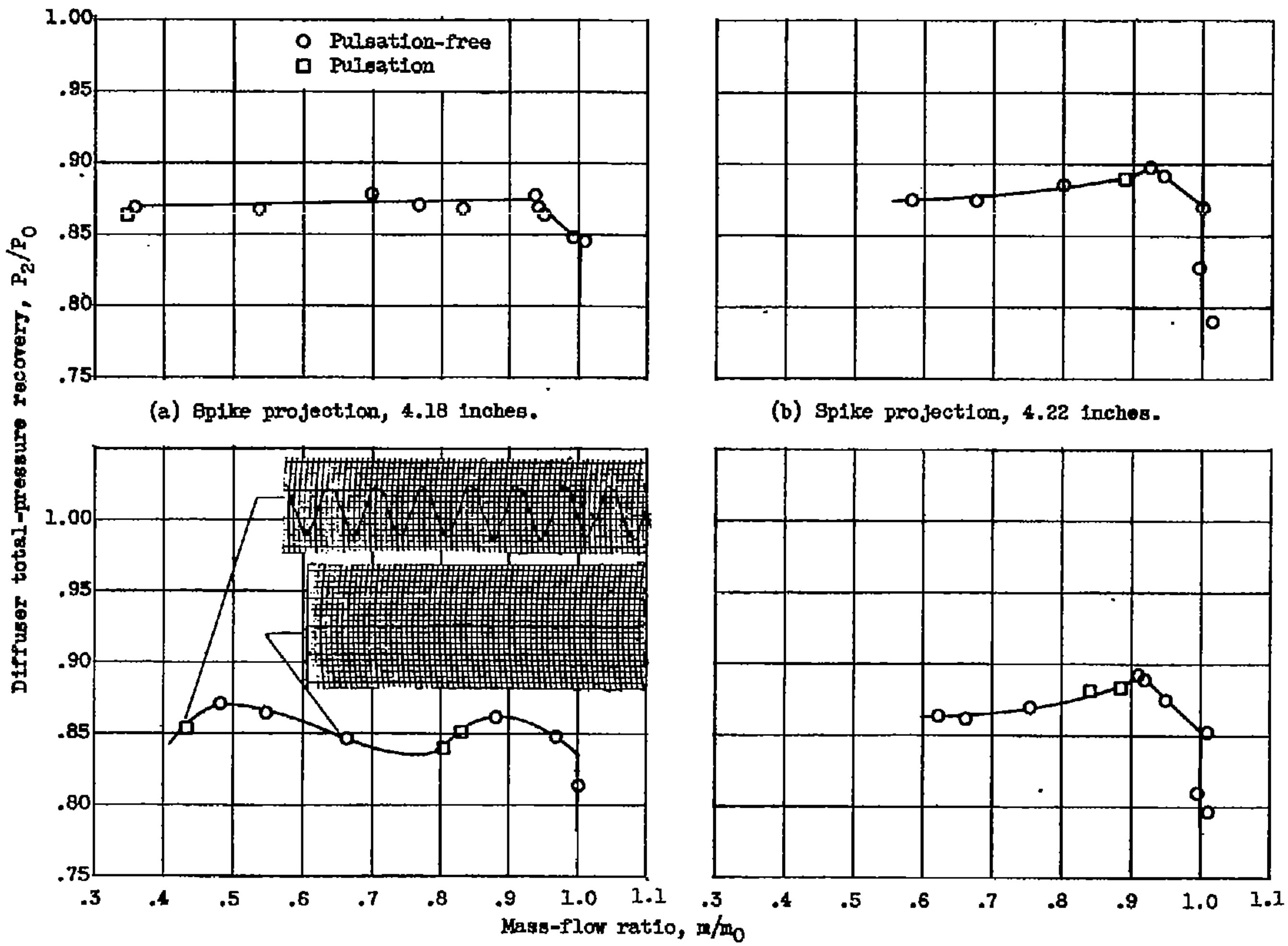
(c) 8-inch ram-jet engine (diffusers illustrated in figs. 3(c), 3(d), and 3(e)) employed in 8- by 6-foot supersonic-tunnel experiments.



V = 5.40 cu ft (small volume) and 12.4 cu ft (large volume)
L_D = 9.17 ft
A_1 = 0.400 sq ft

(d) 16-inch ram-jet engine (diffuser illustrated in fig. 3(f)) employed in 8- by 6-foot supersonic-tunnel experiments.

Figure 4. - Concluded. Schematic diagrams of ram-jet configurations used in diffuser investigations.



(a) Spike projection, 4.18 inches.

(b) Spike projection, 4.22 inches.

(c) Spike projection, 4.27 inches.

(d) Spike projection, 4.32 inches.

Figure 5. - Diffuser pressure recovery as function of engine mass-flow ratio for various diffuser spike projections showing conditions for occurrence of flow pulsations; 16-inch ram jet in supersonic free jet at $M_0 = 1.77$.

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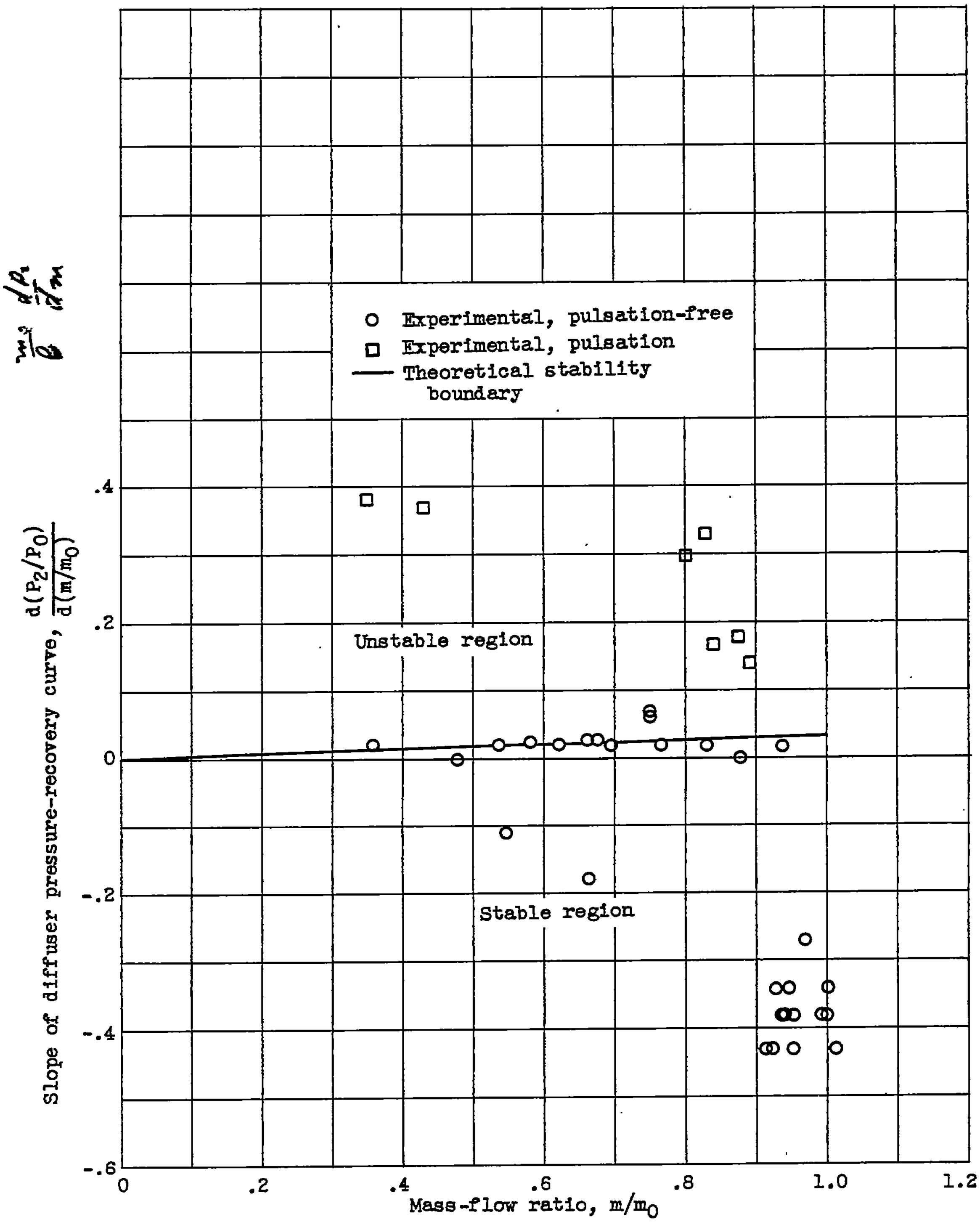

Figure 6. - Comparison of theoretical conditions for resonance stability with occurrence of diffuser flow pulsations; 16-inch ram jet in supersonic free jet at free-stream Mach number of 1.77.

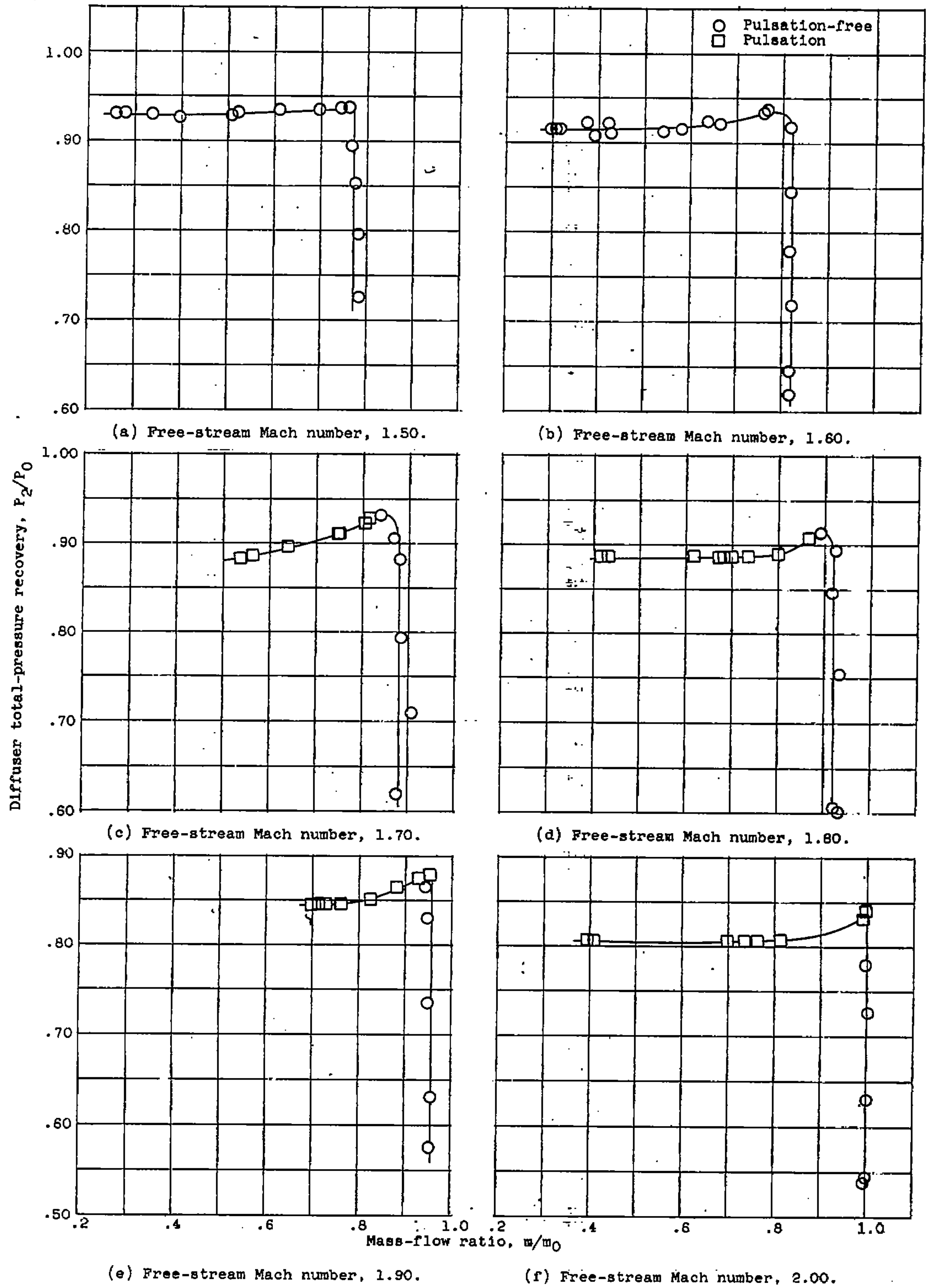

Figure 7. - Diffuser pressure recovery as function of engine mass-flow ratio for ram jet with small volume showing occurrence of flow pulsations at various free-stream Mach numbers; 16-inch ram jet in 8- by 6-foot supersonic tunnel.

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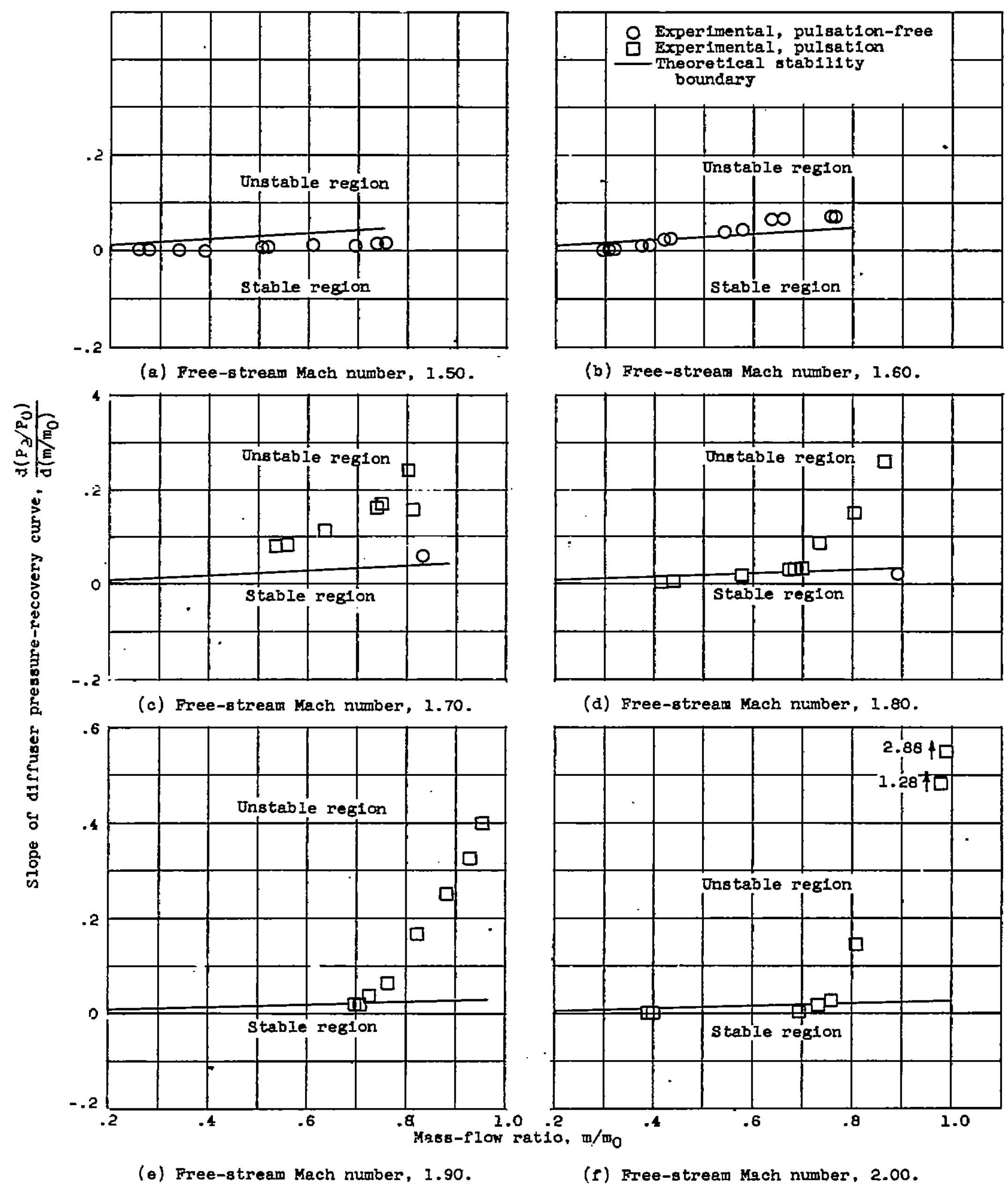

Figure 8. - Comparison of theoretical conditions for resonance stability with occurrence of diffuser flow pulsations for ram jet with small volume; 16-inch ram jet in 8- by 6-foot supersonic tunnel.

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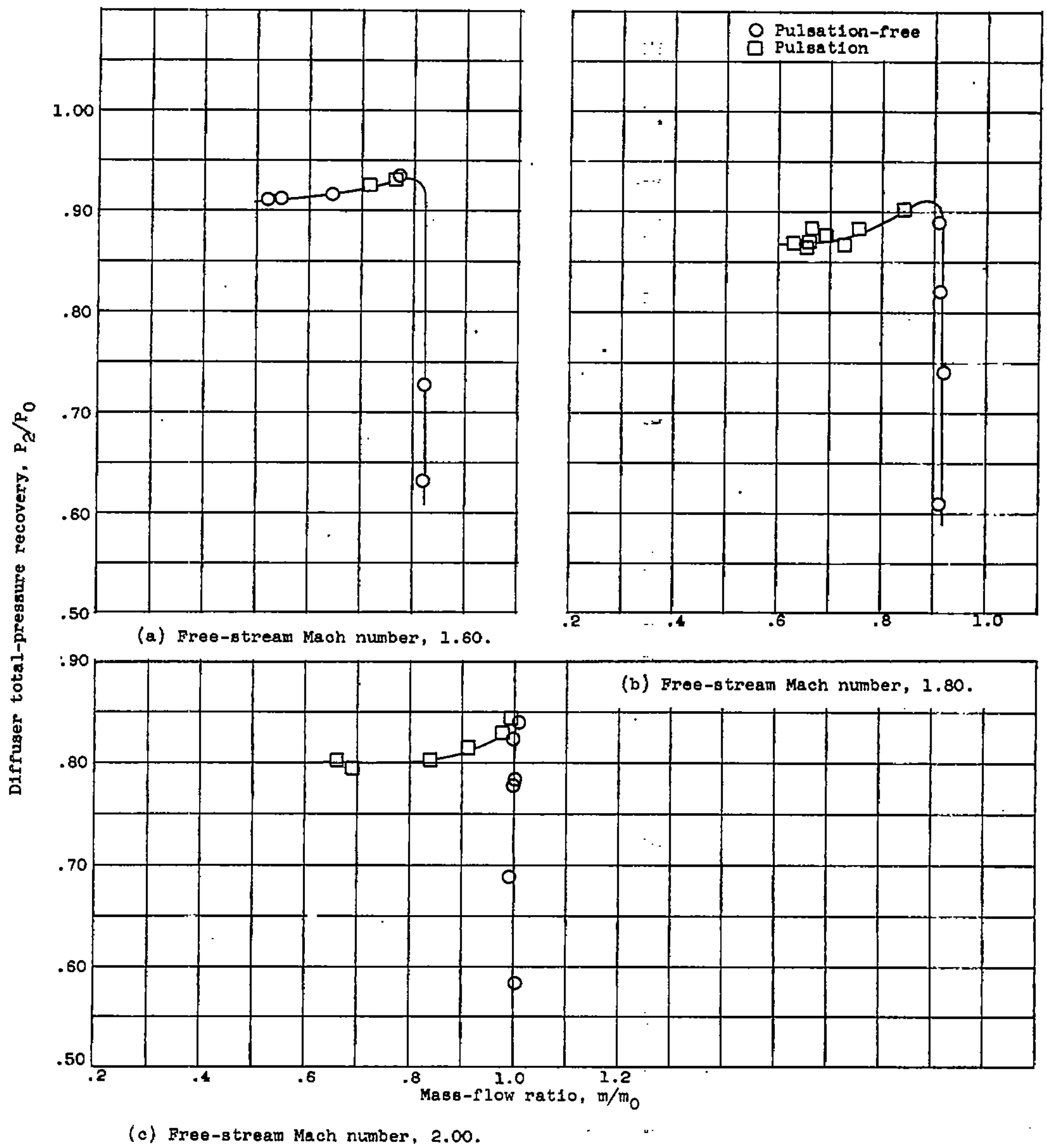

Figure 9. - Diffuser pressure recovery as function of mass-flow ratio for ram jet with large volume showing occurrence of flow pulsations at various free-stream Mach numbers; 16-inch ram jet in 8- by 6-foot supersonic tunnel.

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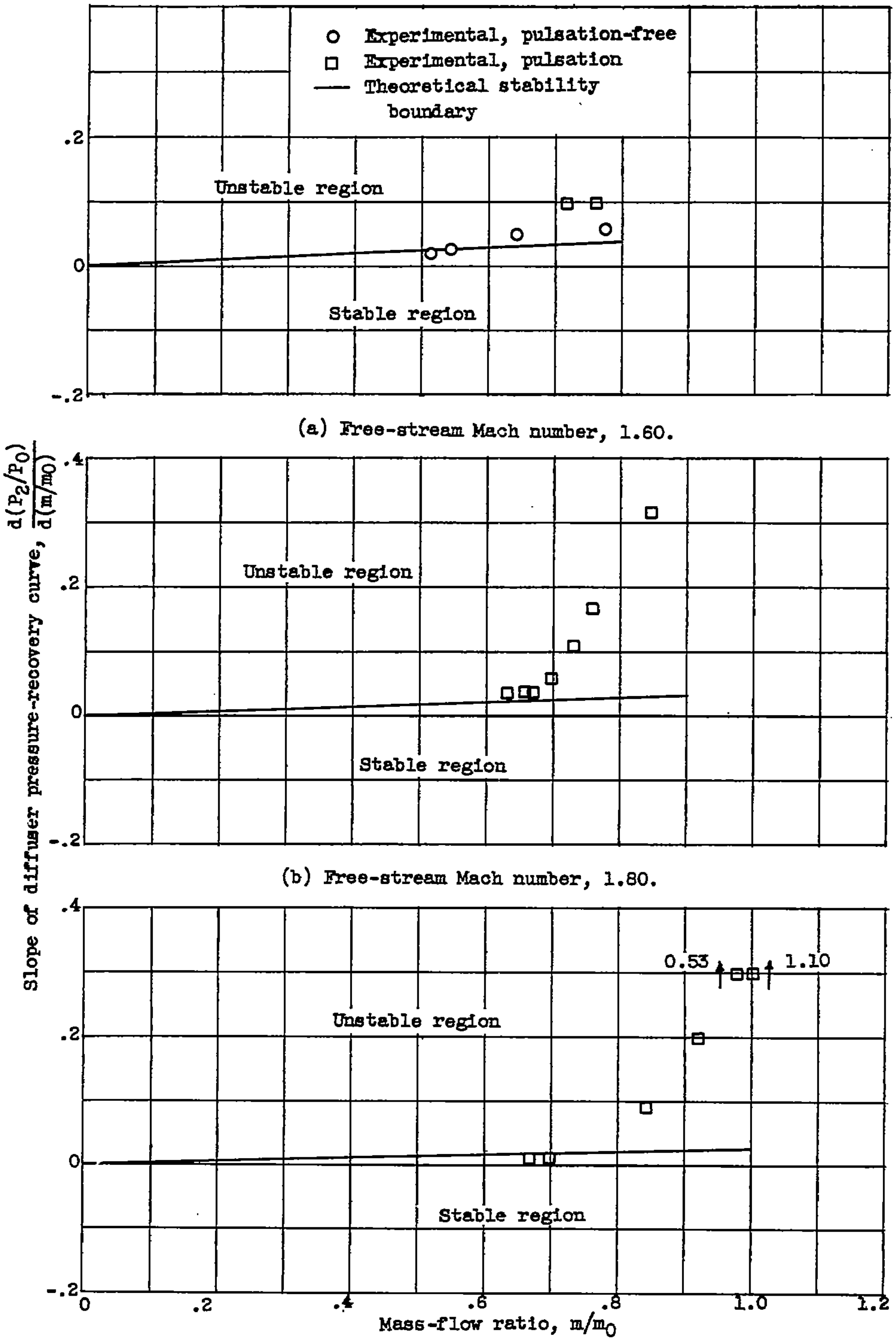
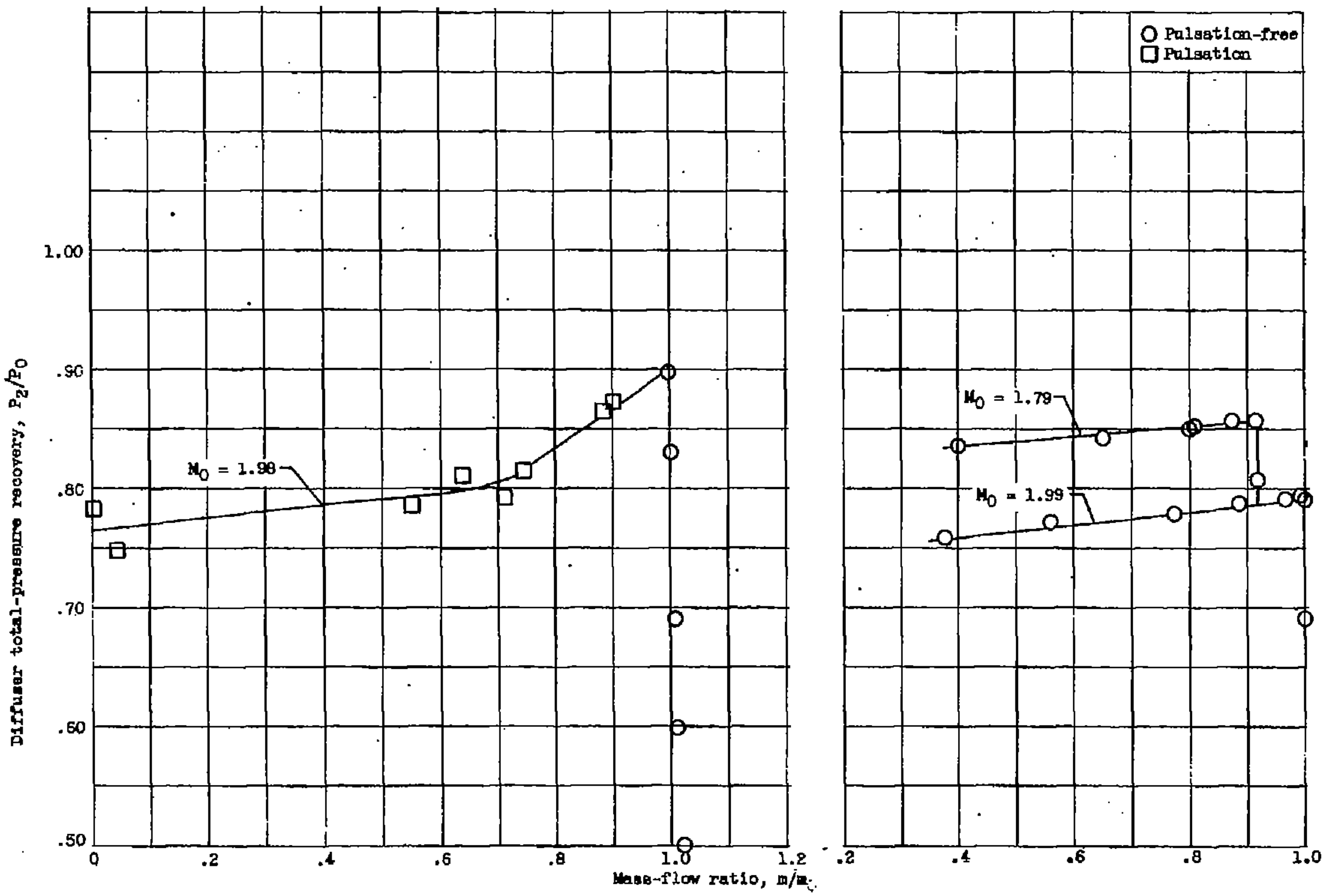


(a) Free-stream Mach number, 1.60.

(b) Free-stream Mach number, 1.80.

(c) Free-stream Mach number, 2.00.

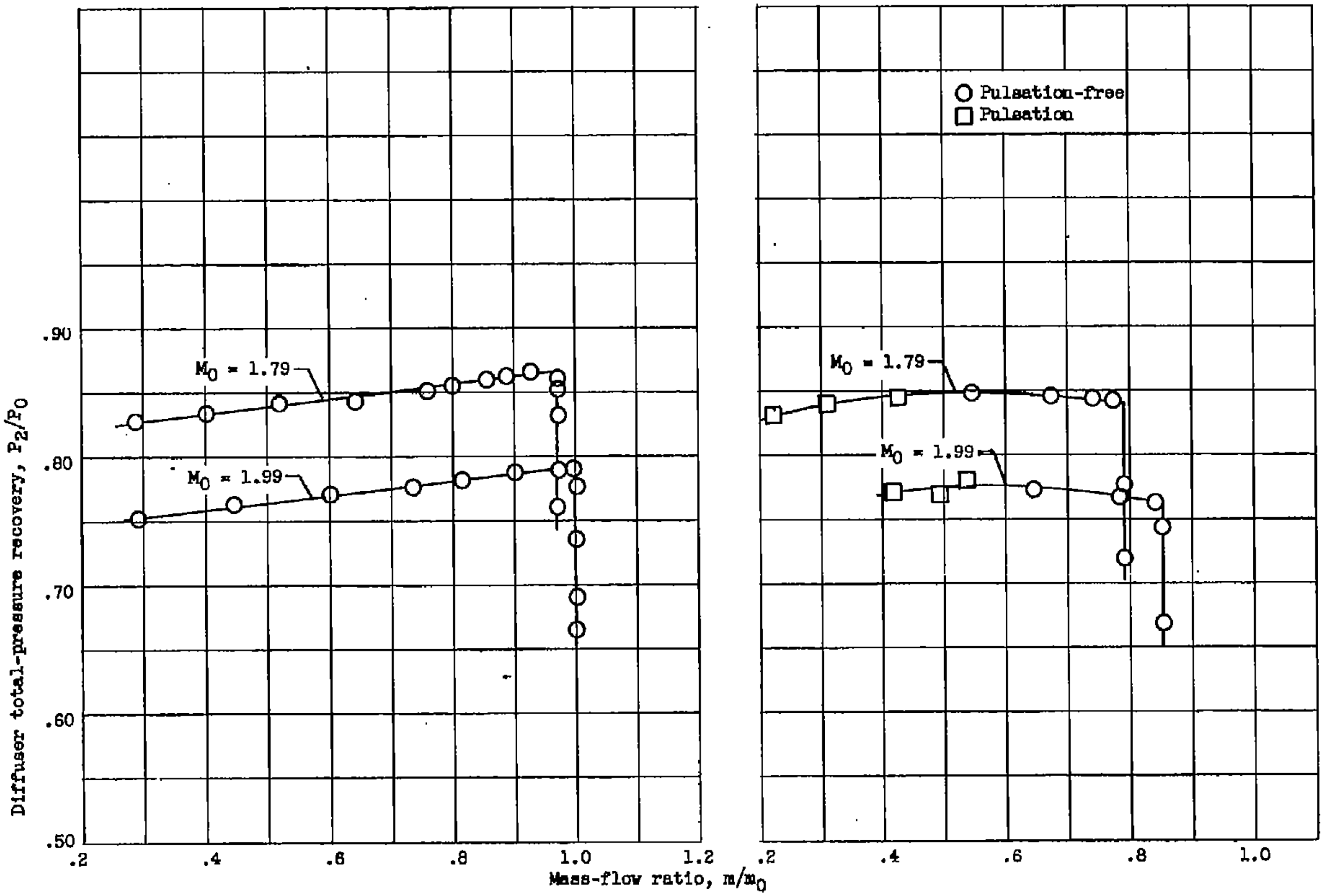
Figure 10. - Comparison of theoretical conditions for resonance stability with occurrence of diffuser flow pulsations for ram jet with large volume; 16-inch ram jet in 8- by 6-foot supersonic tunnel.



(a) Single-shock 40° cone; external compression; sharp-edged inlet; 20-inch supersonic tunnel.

(b) Single-shock 50° cone; external and internal compression; round-edged inlet; 8- by 6-foot supersonic tunnel.

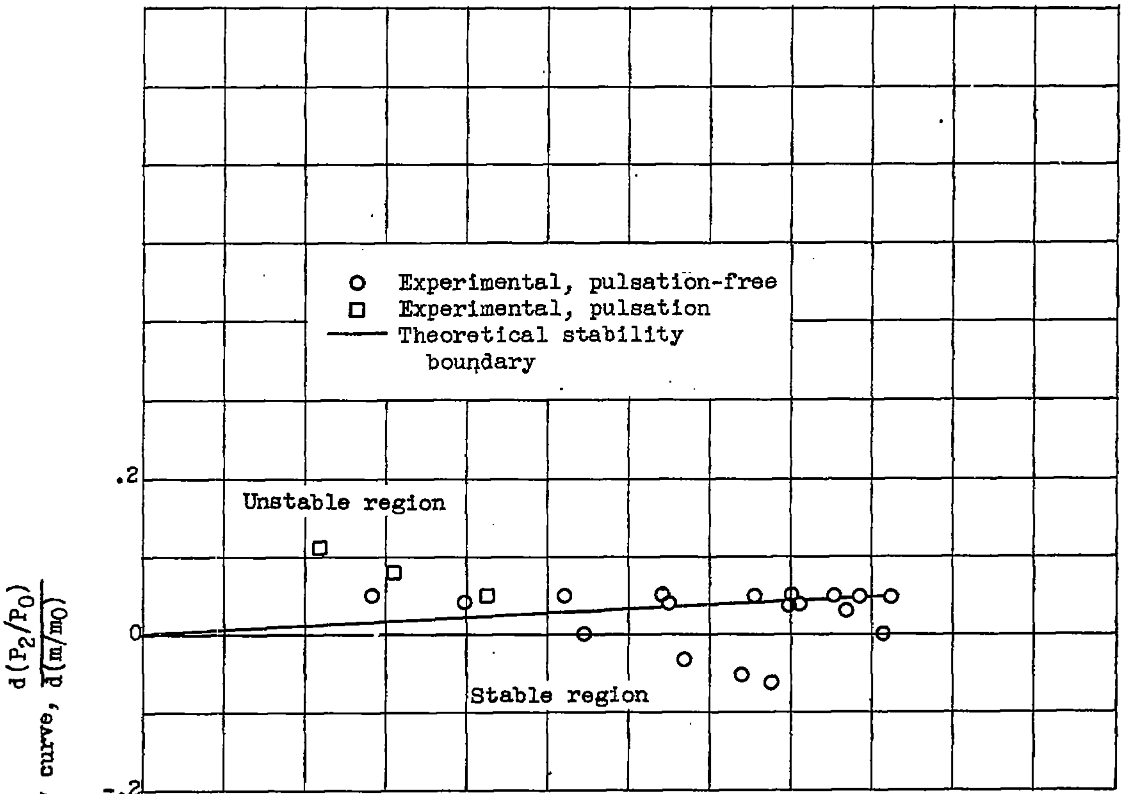
Figure 11. - Diffuser pressure recovery as function of mass-flow ratio for various diffuser designs showing occurrence of flow pulsations; 8-inch ram jets.



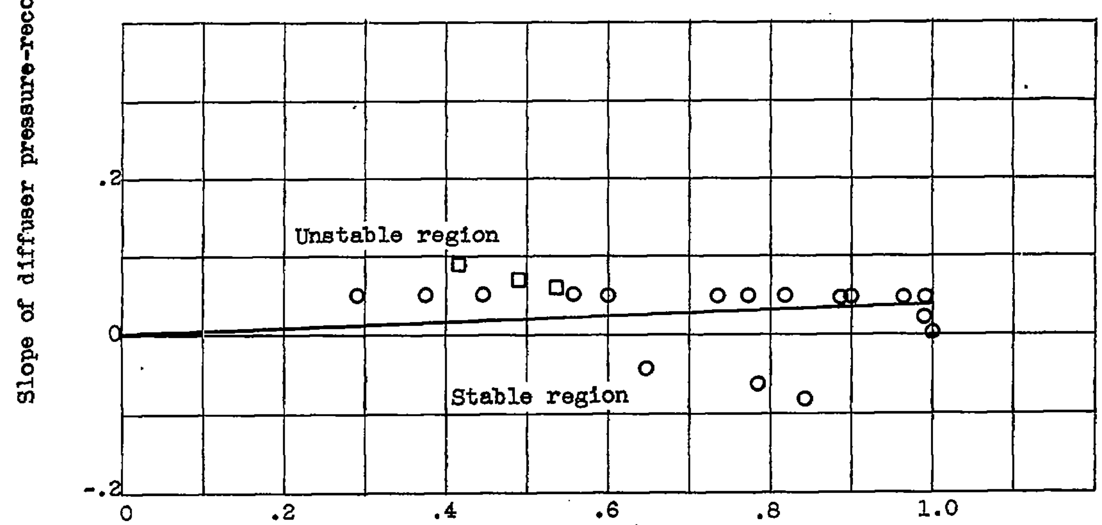
(c) Single-shock 50° cone; external compression; sharp-edged inlet; 8- by 6-foot supersonic tunnel.

(d) Isentropic compression spike; external compression; round-edged inlet; 8- by 6-foot supersonic tunnel.

Figure 11. - Concluded. Diffuser pressure recovery as function of mass-flow ratio for various diffuser designs showing occurrence of flow pulsations; 8-inch ram jets.



(a) Free-stream Mach number, 1.79.



(b) Free-stream Mach number, 1.99.

Figure 12. - Comparison of theoretical conditions for resonance stability with occurrence of diffuser flow pulsations for various diffuser designs; 8-inch ram jet in 8- by 6-foot supersonic tunnel.

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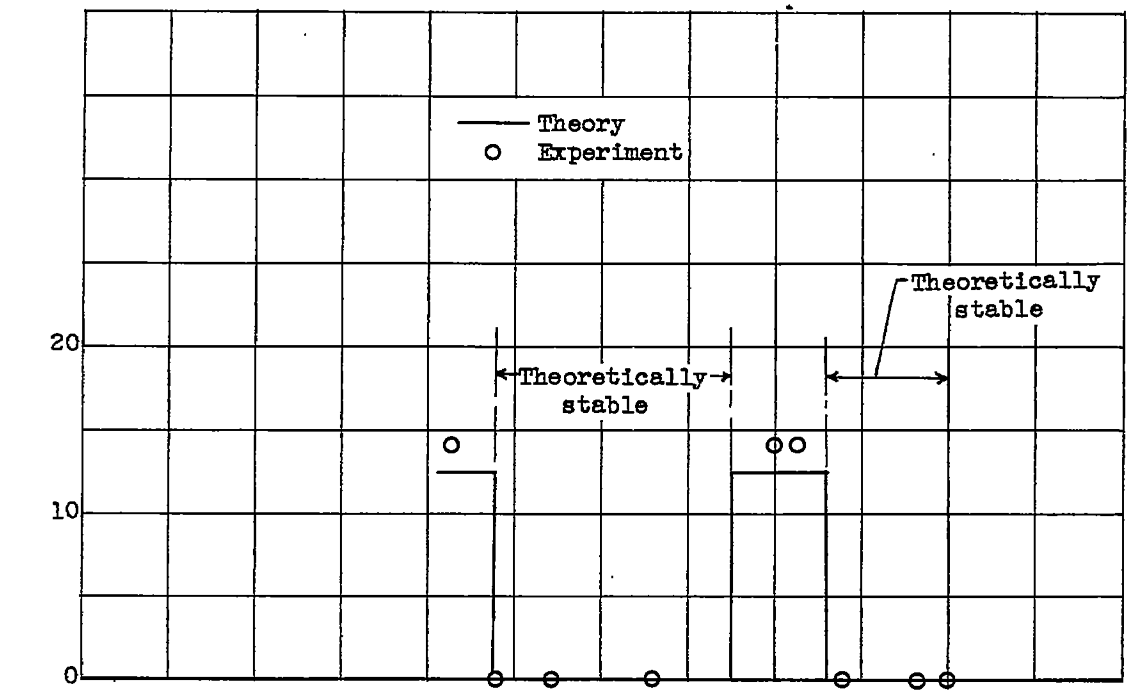
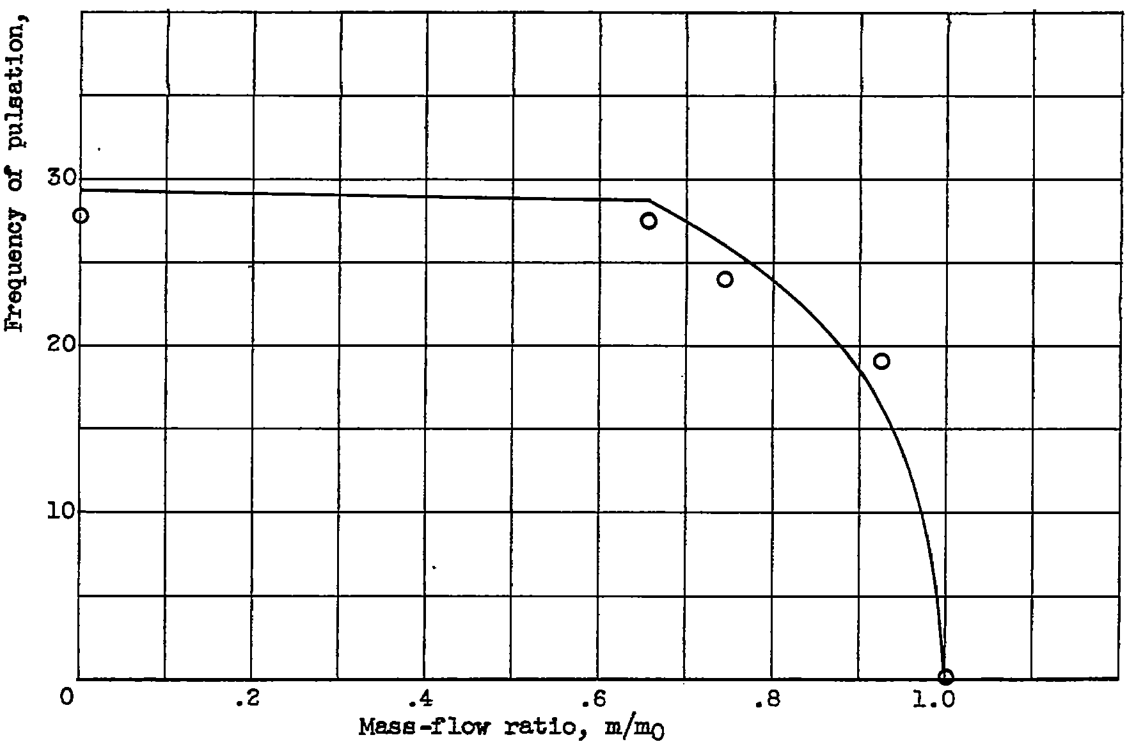


(a) 16-inch ram jet in supersonic free jet at free-stream Mach number of 1.77.



(b) 8-inch ram jet in 20-inch supersonic tunnel at free-stream Mach number of 1.98.

Figure 13. - Frequency of pulsations.

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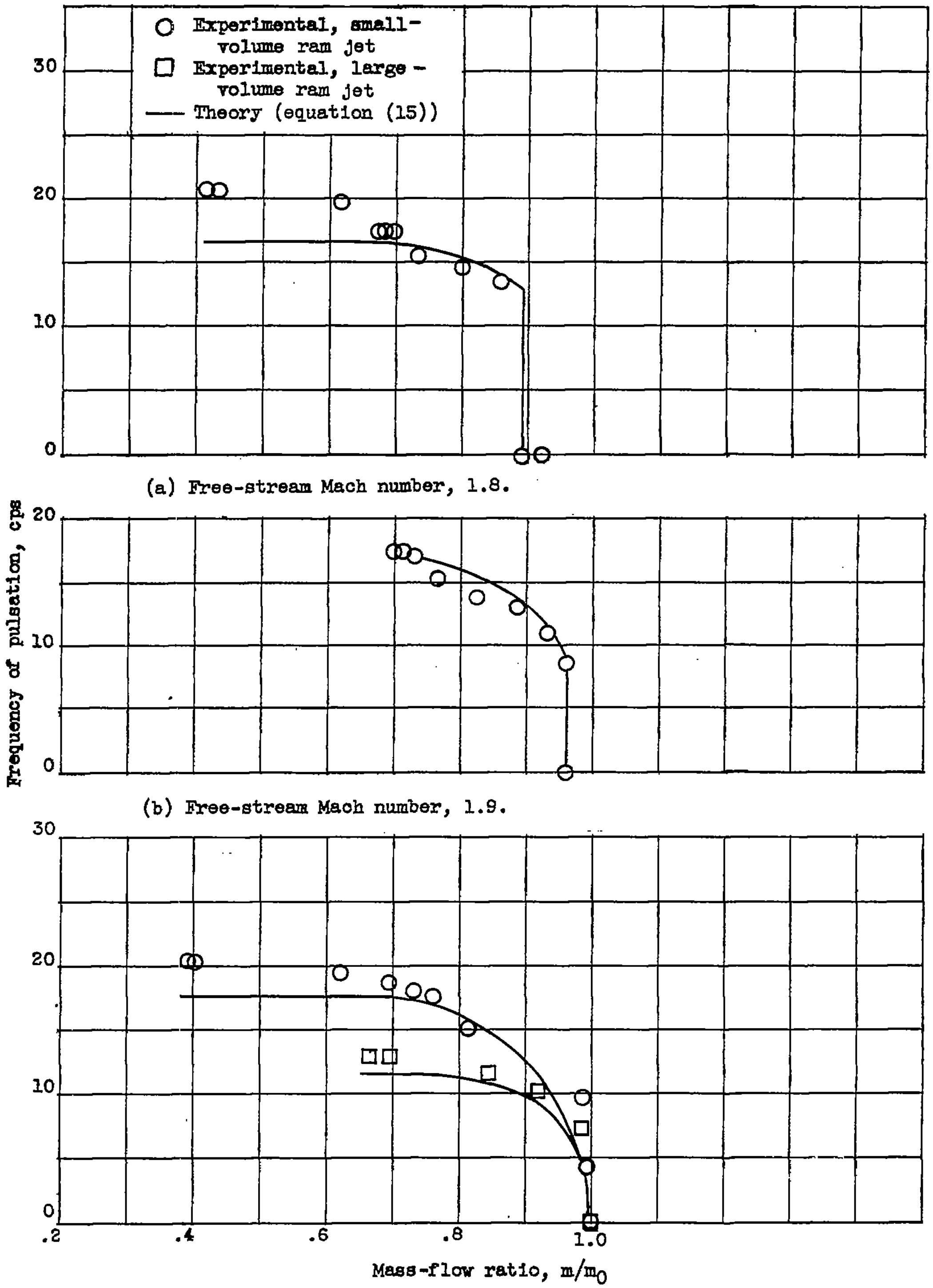
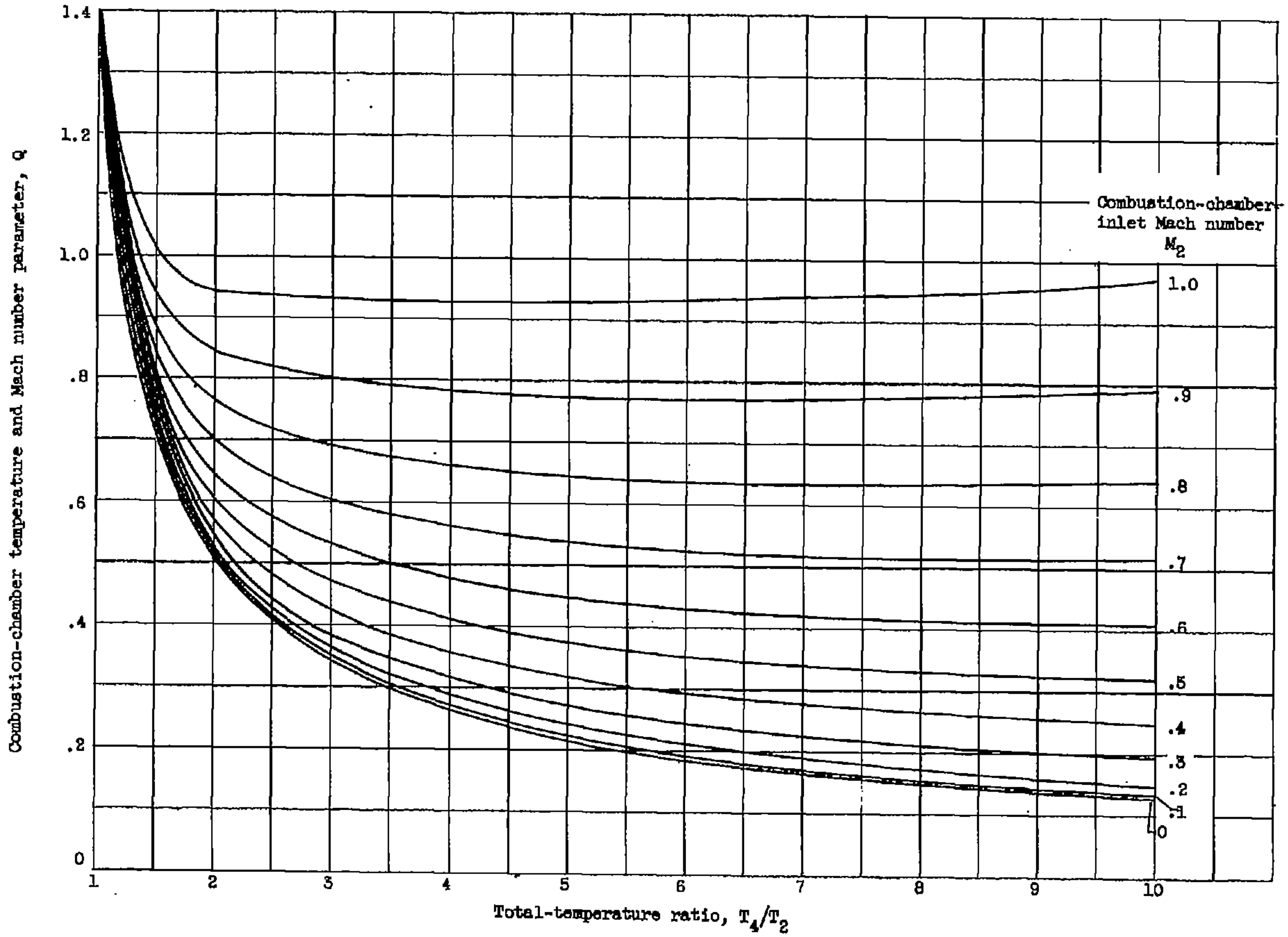
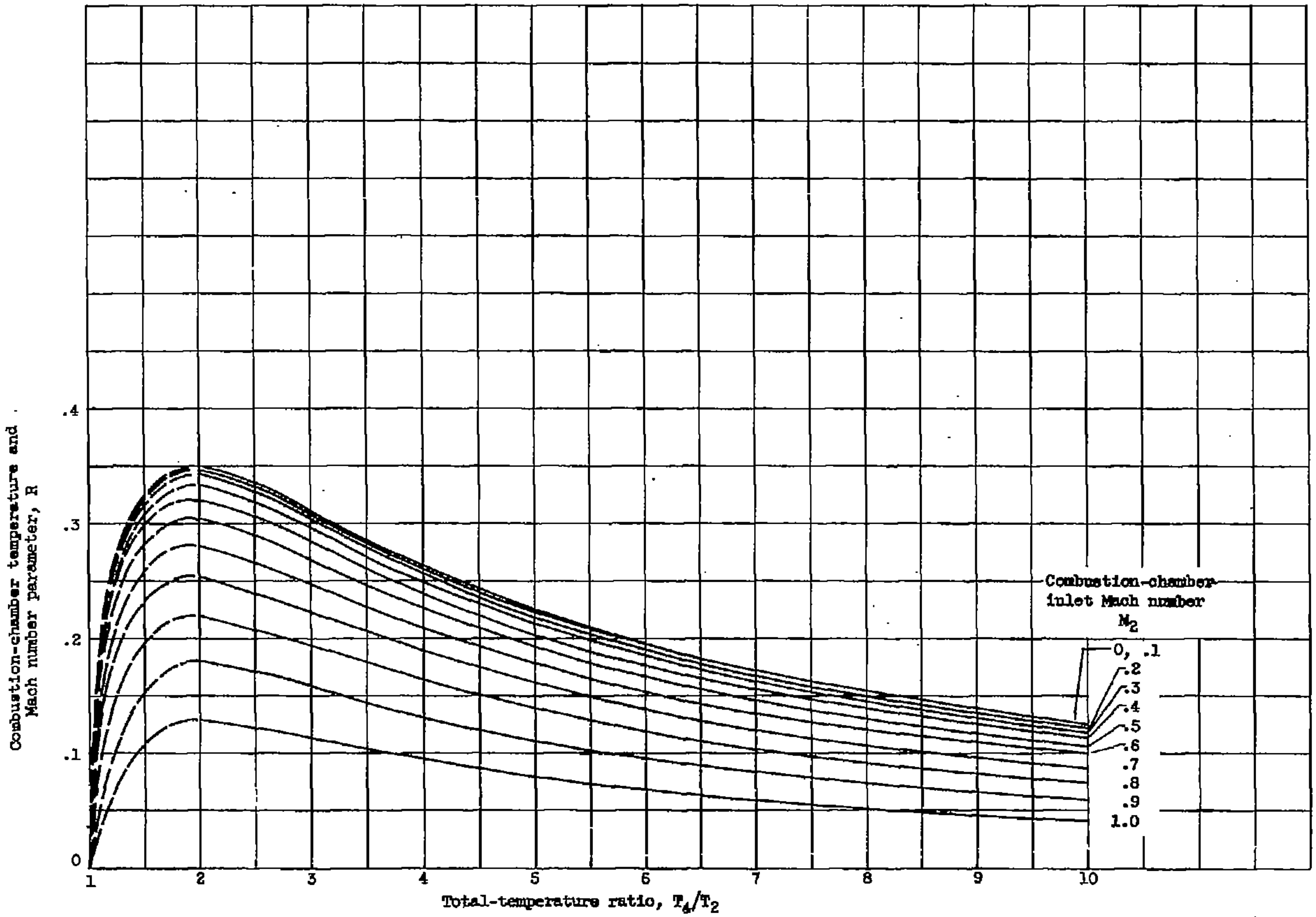


Figure 14. - Frequency of pulsation at various Mach numbers for 16-inch ram jet with two different volumes; 8- by 6-foot supersonic tunnel.



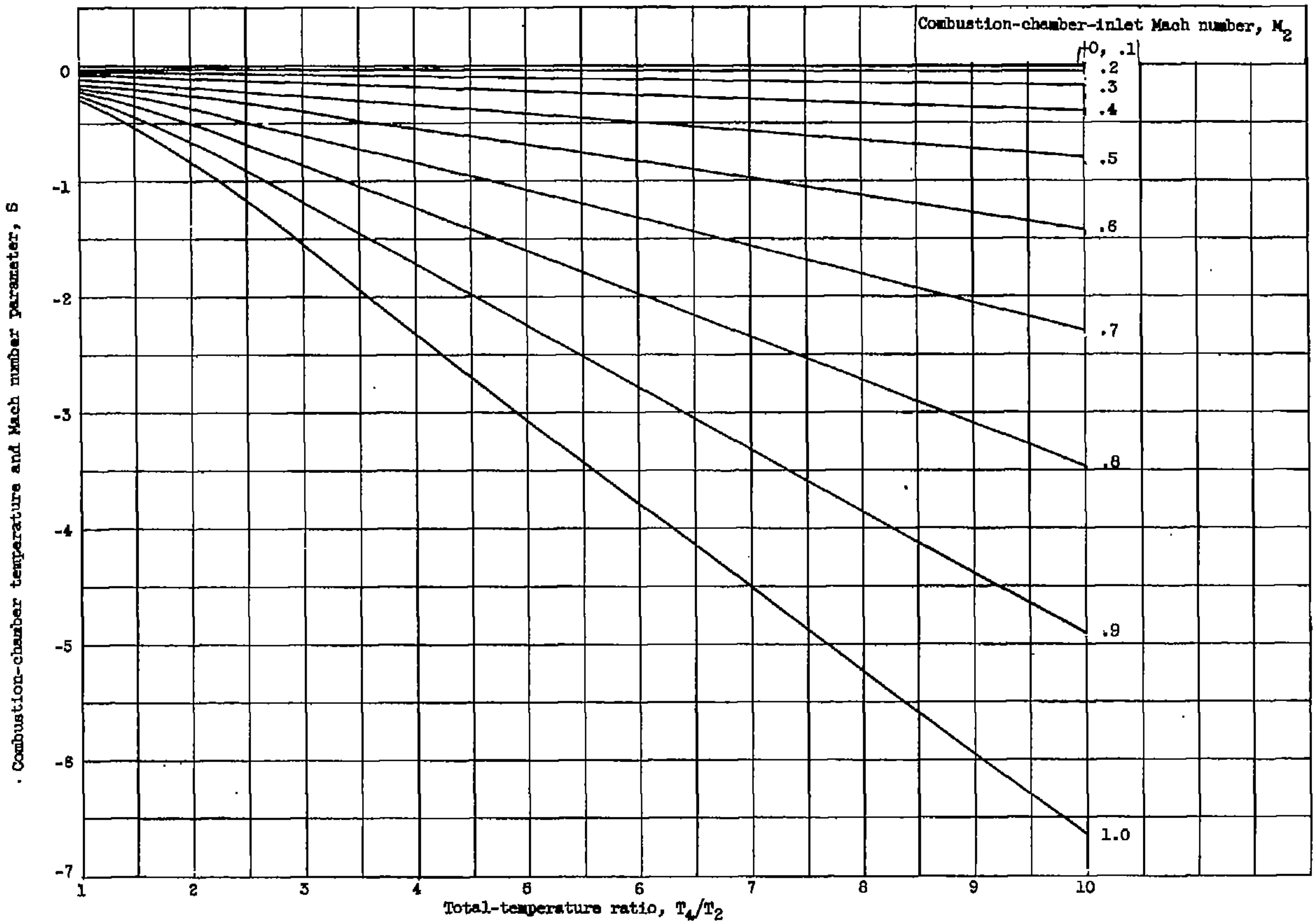
(a) Combustion-chamber temperature and Mach number parameter, Q.

Figure 15. - Parameters for determining theoretical diffuser stability with heat addition. $\gamma_2 = 1.4$; $\gamma_4 = \gamma_2 - 0.03\ (\tau - 1)$.



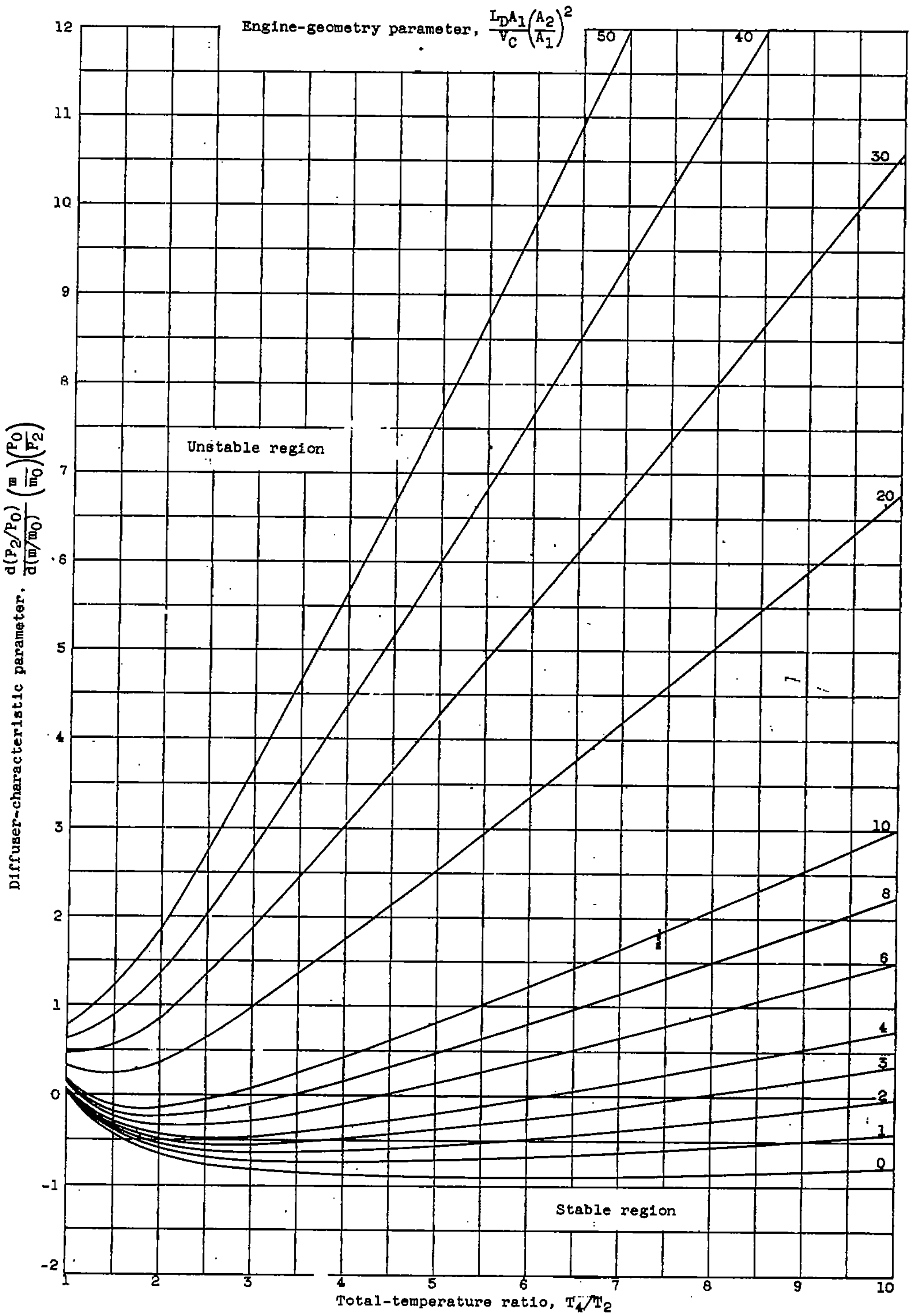
(b) Combustion-chamber temperature and Mach number parameter, R.

Figure 15. - Continued. Parameters for determining theoretical diffuser stability with heat addition. $\gamma_2 = 1.4$, $\gamma_4 = \gamma_2 - 0.03\ (\tau - 1)$.



(c) Combustion-chamber temperature and Mach number parameter, S.

Figure 15. - Concluded. Parameters for determining theoretical diffuser stability with heat addition. $\gamma_2 = 1.4$, $\gamma_4 = \gamma_2 - 0.03\ (\tau - 1)$.



(a) Fixed value of M_2 (variable engine-outlet area); $M_2 = 0.2$.

Figure 16. - Theoretical stability criterions with heat addition. $V_D/V_C = 0$; $\gamma_2 = 1.4$; $\gamma_4 = \gamma_2 - 0.03$ ($\underline{\ }$ 1).

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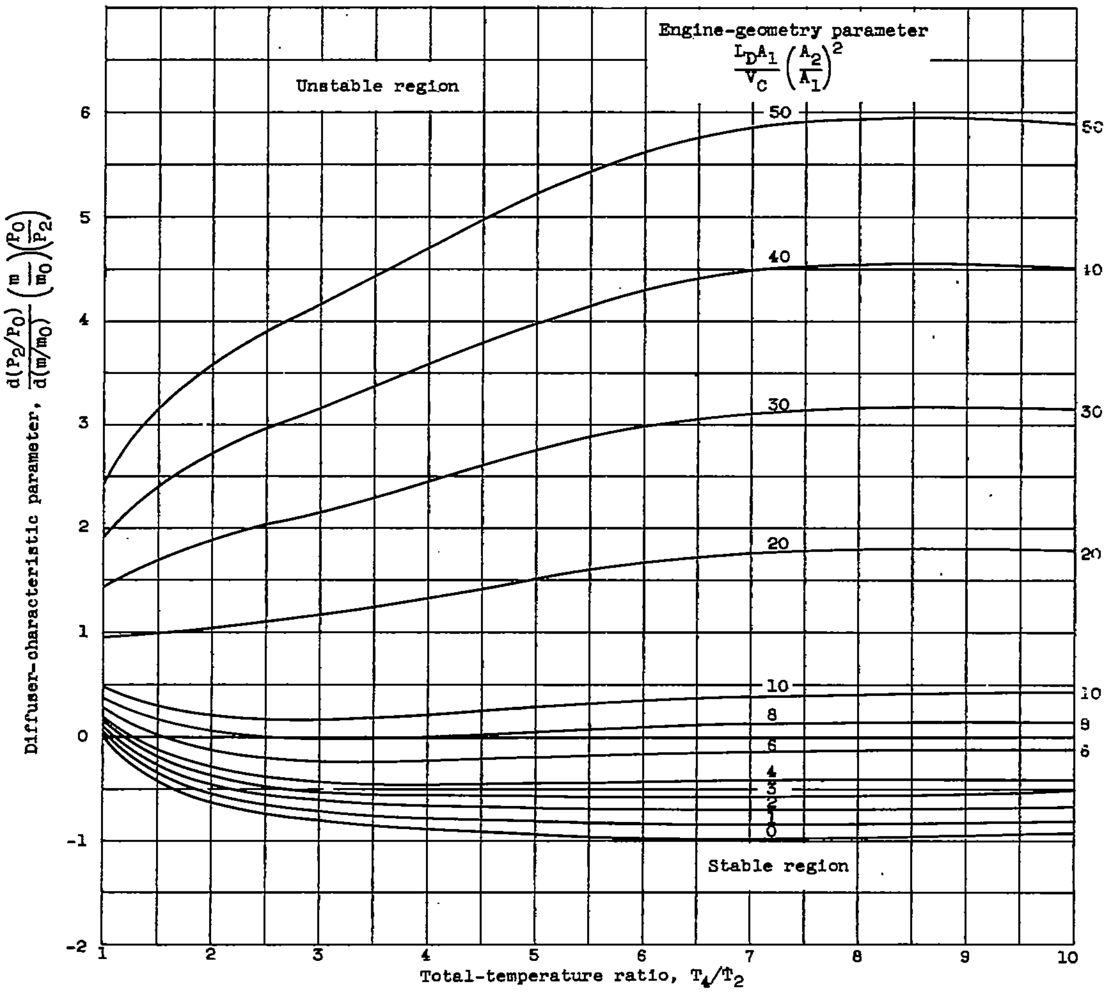
CT-7 back



(b) Fixed value of $M_2\sqrt{\tau}$ (fixed engine-outlet area); $M_2\sqrt{\tau} = 0.36$.

Figure 16. - Concluded. Theoretical stability criterions with heat addition. $V_D/V_C = 0$; $\gamma_2 = 1.4$; $\gamma_4 = \gamma_2 - 0.03$ (. - 1).

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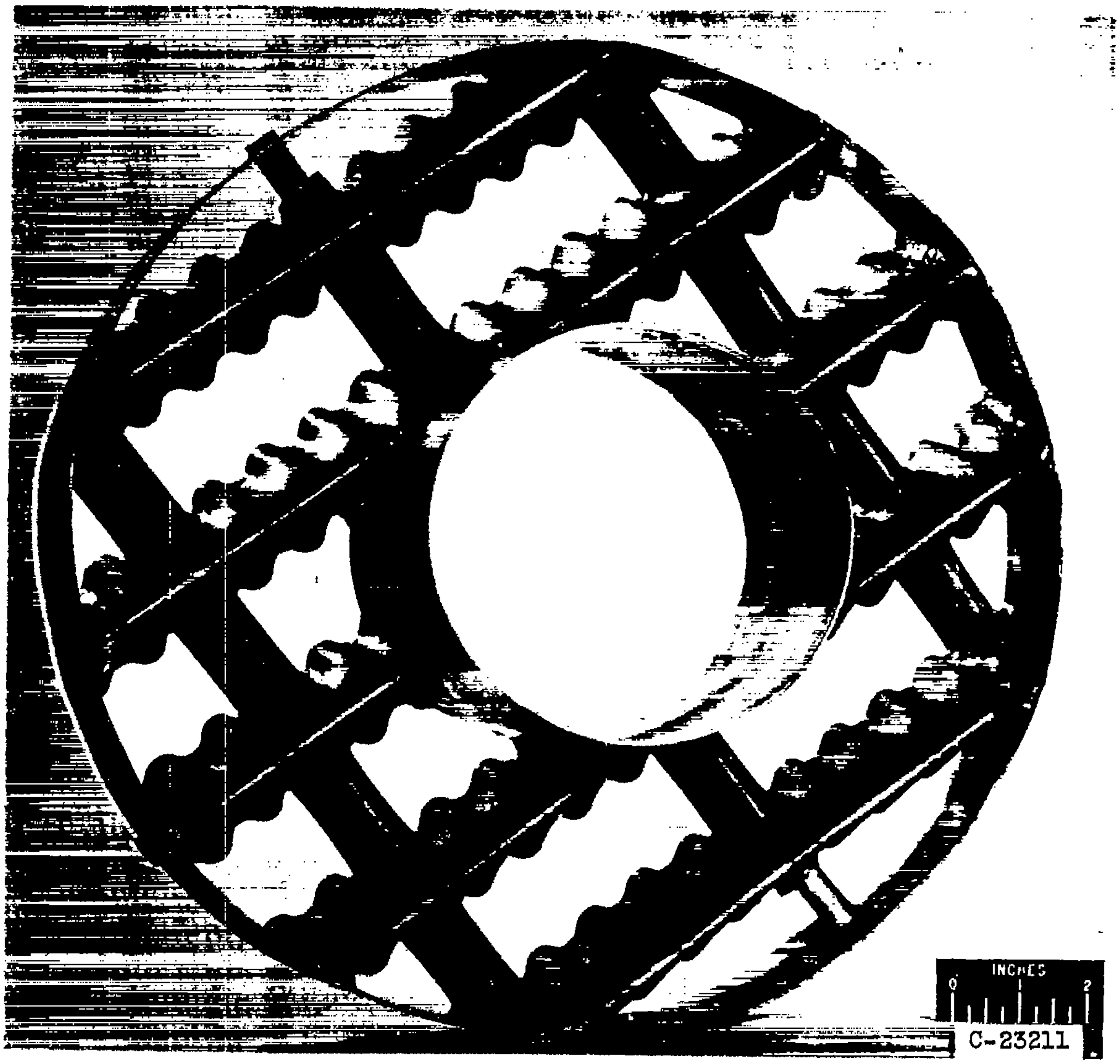

(a) Upstream view of corrugated-gutter flame holder.

Figure 17. - Ram-jet burner.

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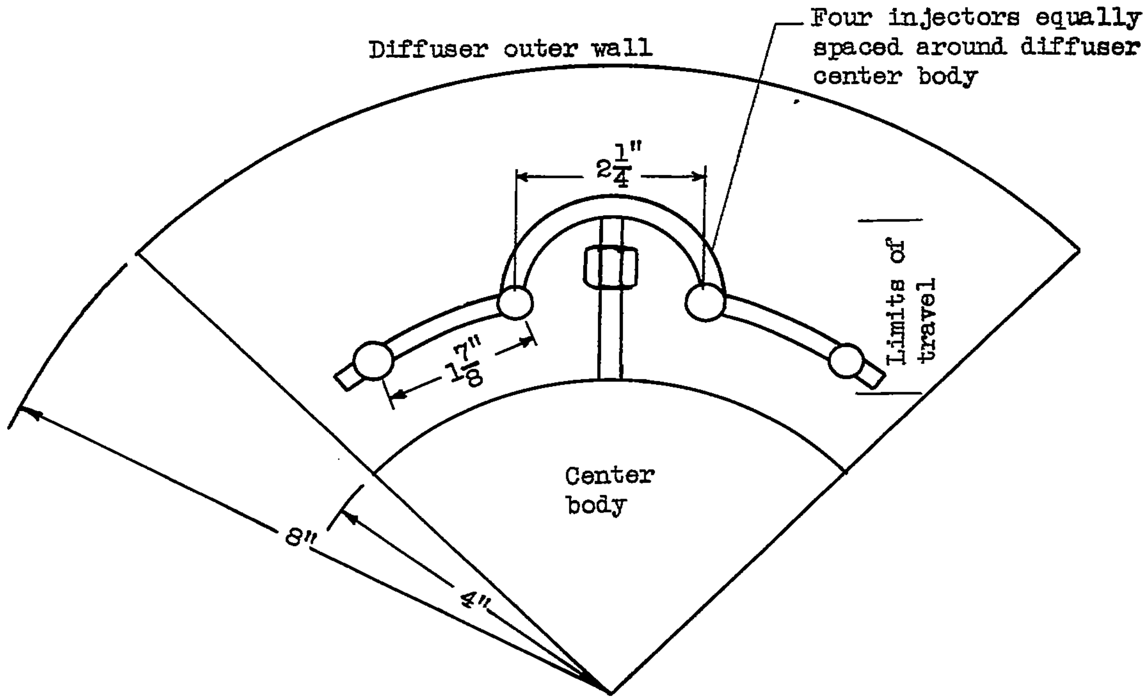

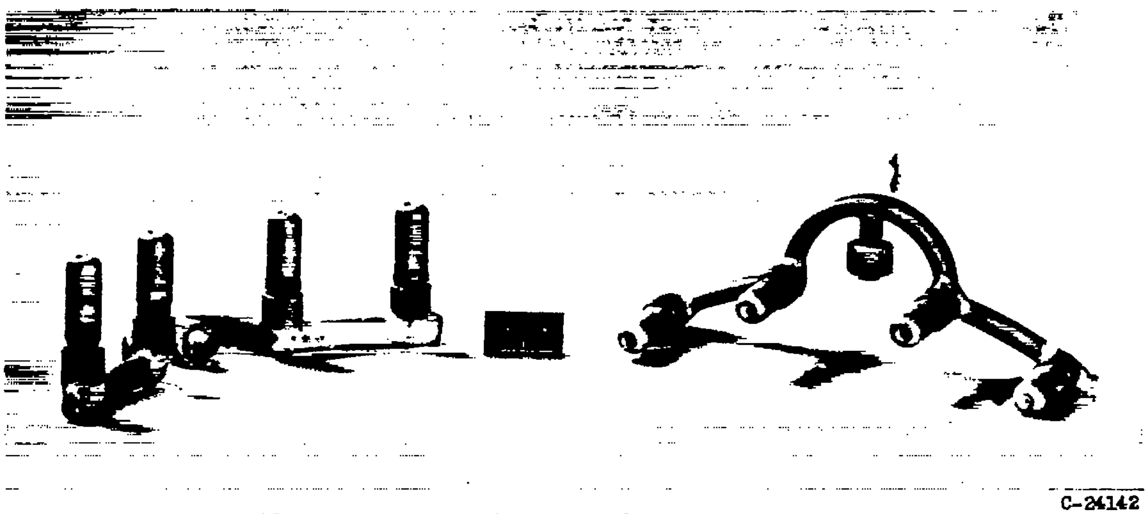

(b) Spray-nozzle fuel injector.

Figure 17. - Concluded. Ram-jet burner.

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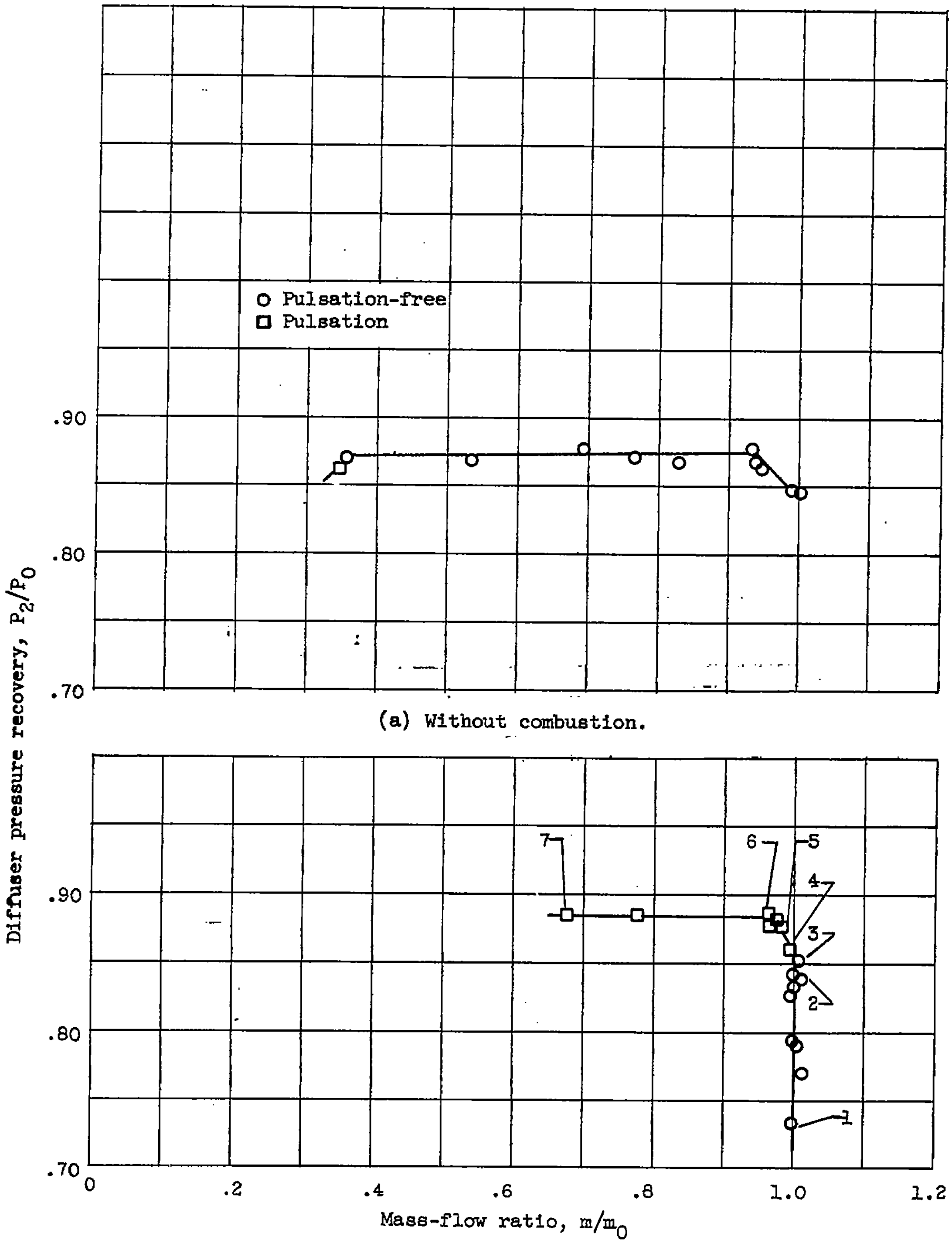

Figure 18. - Effect of heat addition on flow pulsations of 16-inch ram jet using gasoline as fuel. Free-stream Mach number, 1.77.

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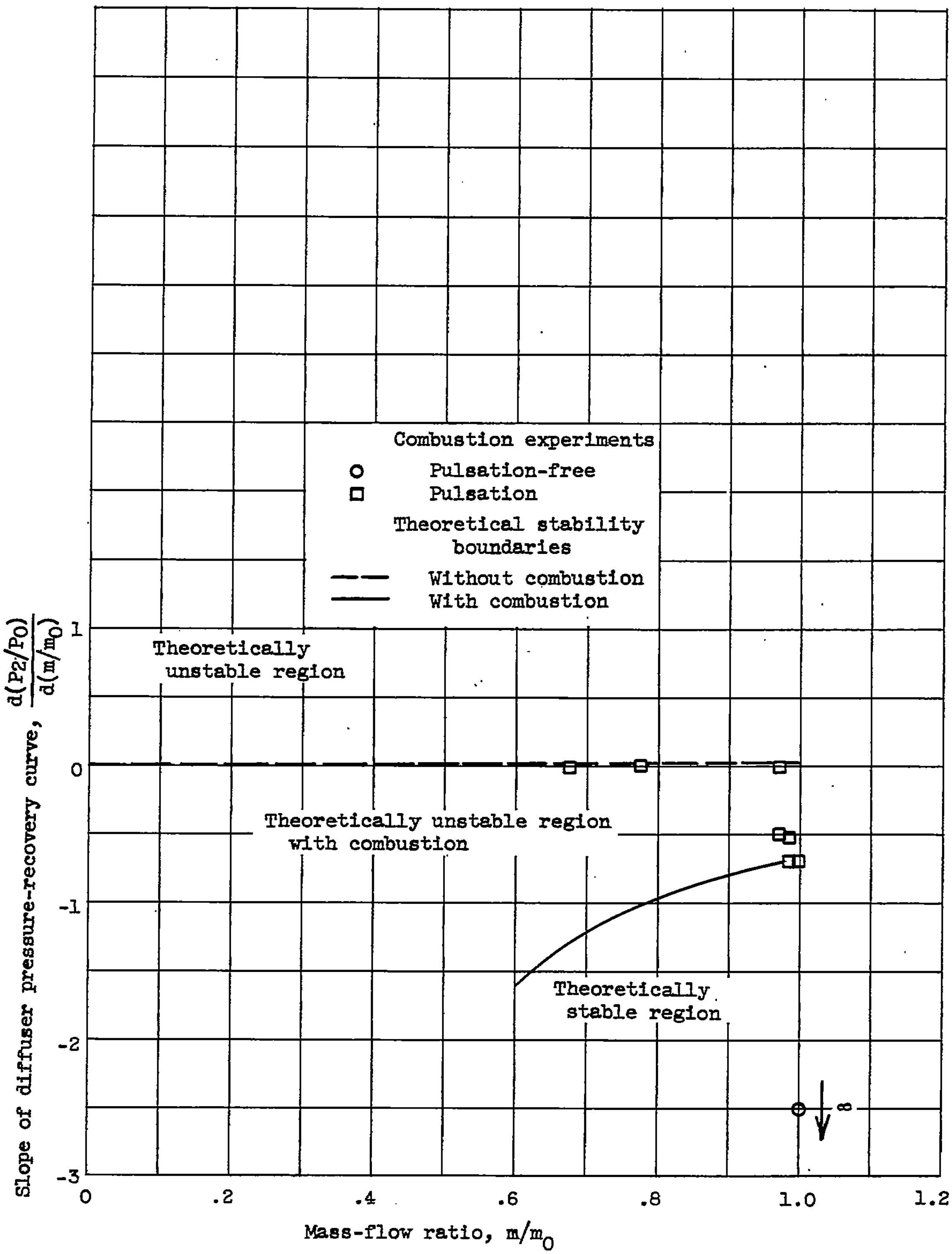

Figure 19. - Theoretical and experimental stability conditions of 16-inch ram jet using gasoline as fuel. Free-stream Mach number, 1.77.

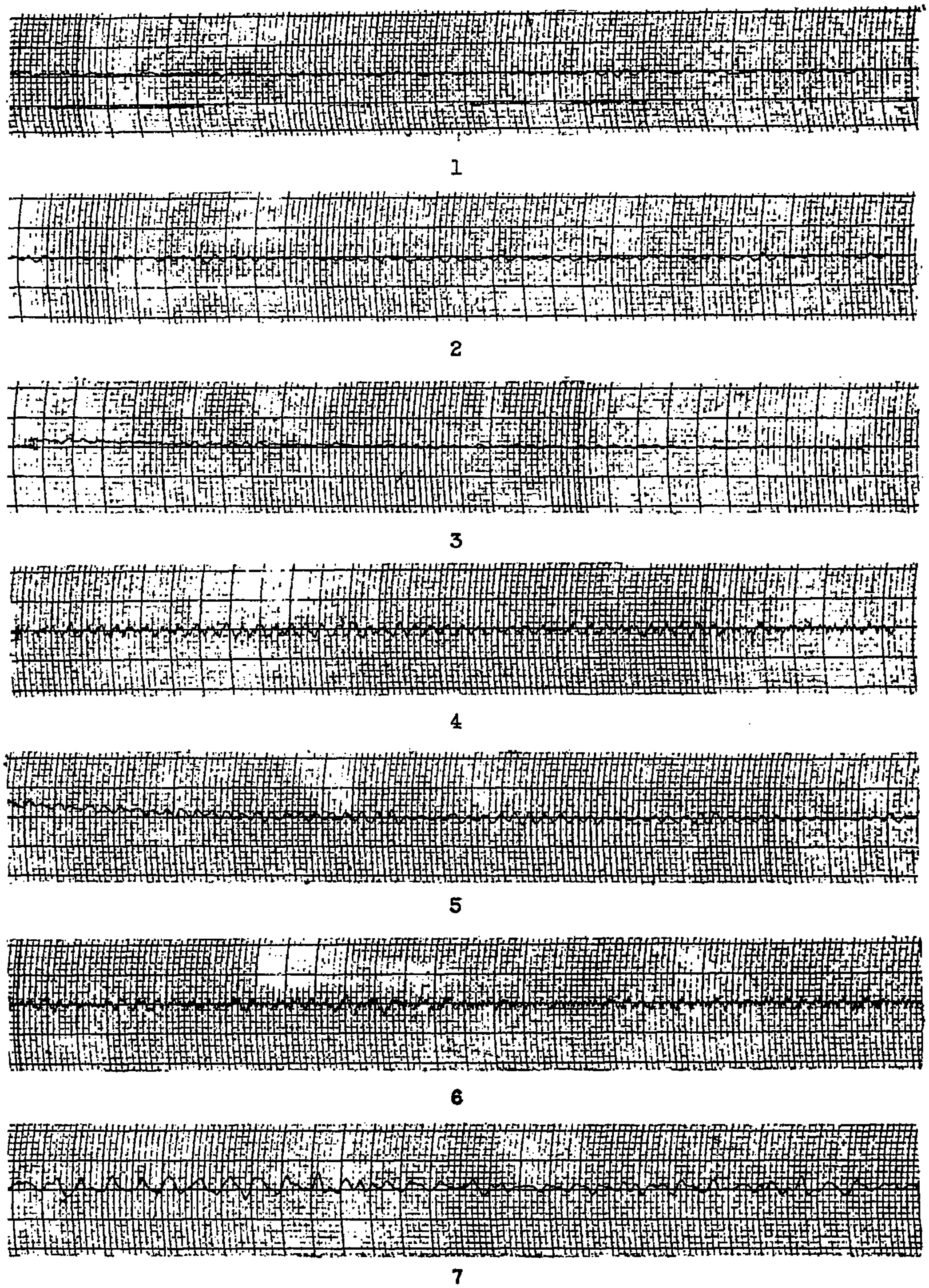

Figure 20. - Pressure oscillation traces in 16-inch ram jet at various mass-flow ratios using gasoline as fuel. Free-stream Mach number, 1.77.

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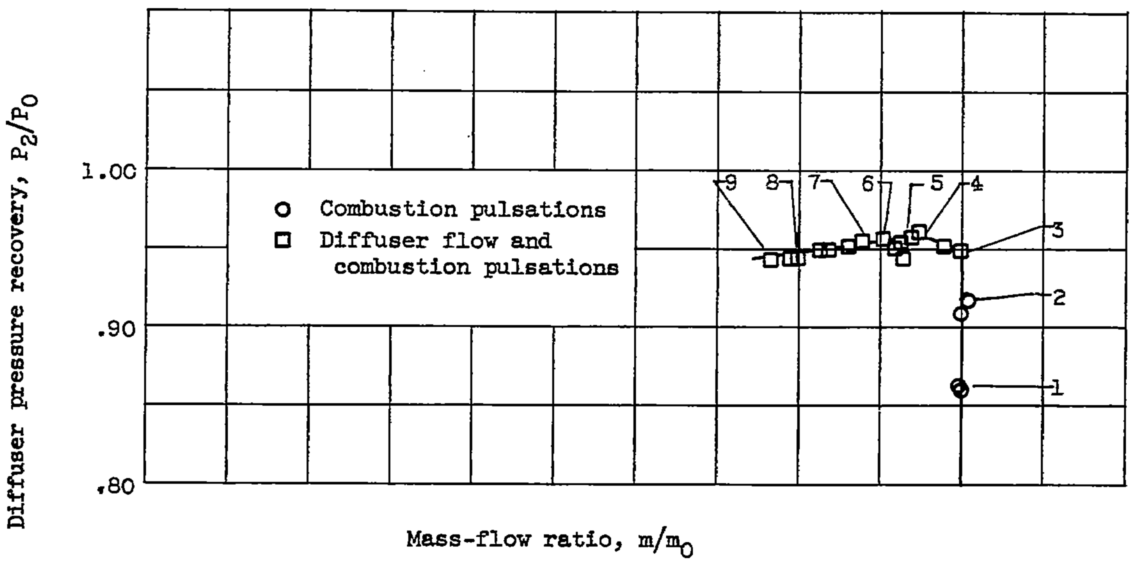


Figure 21. - Occurrence of flow pulsations in 16-inch ram jet using kerosene - propylene-oxide fuel blend. Free-stream Mach number, 1.58.

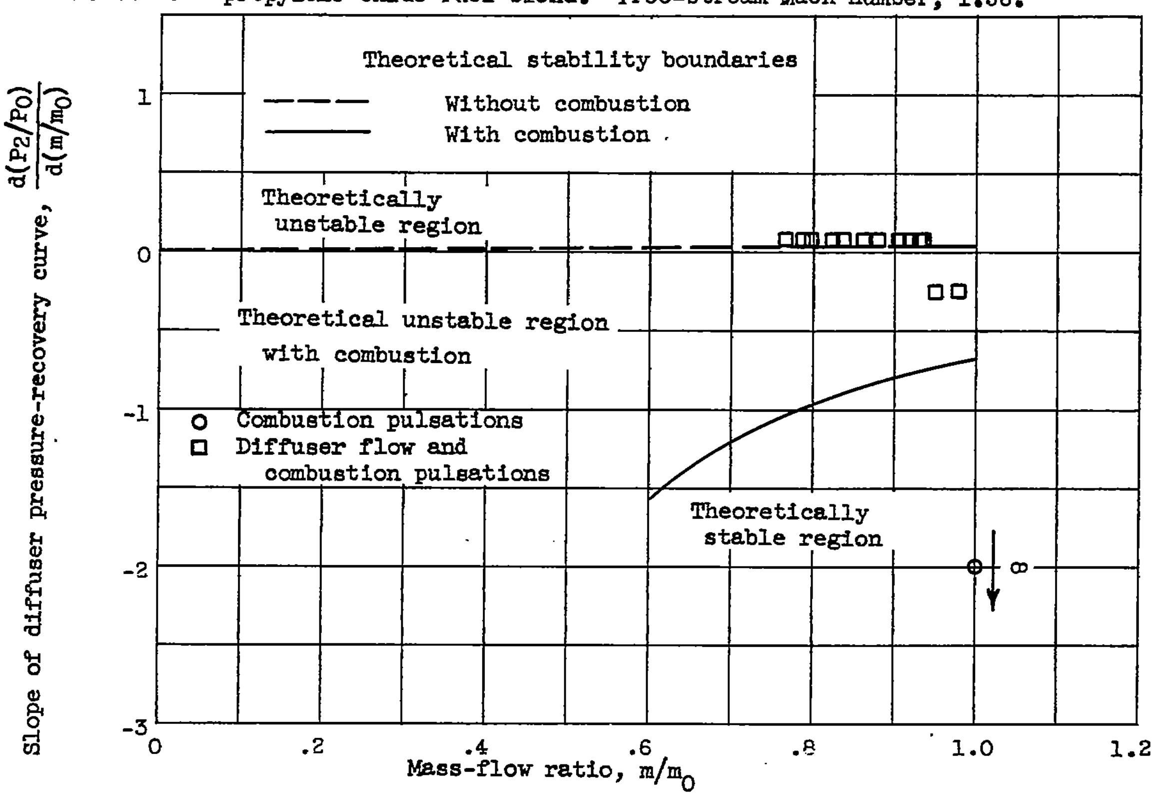


Figure 22. - Theoretical and experimental stability conditions of 16-inch ram jet using kerosene - propylene-oxide fuel blend. Free-stream Mach number, 1.58.

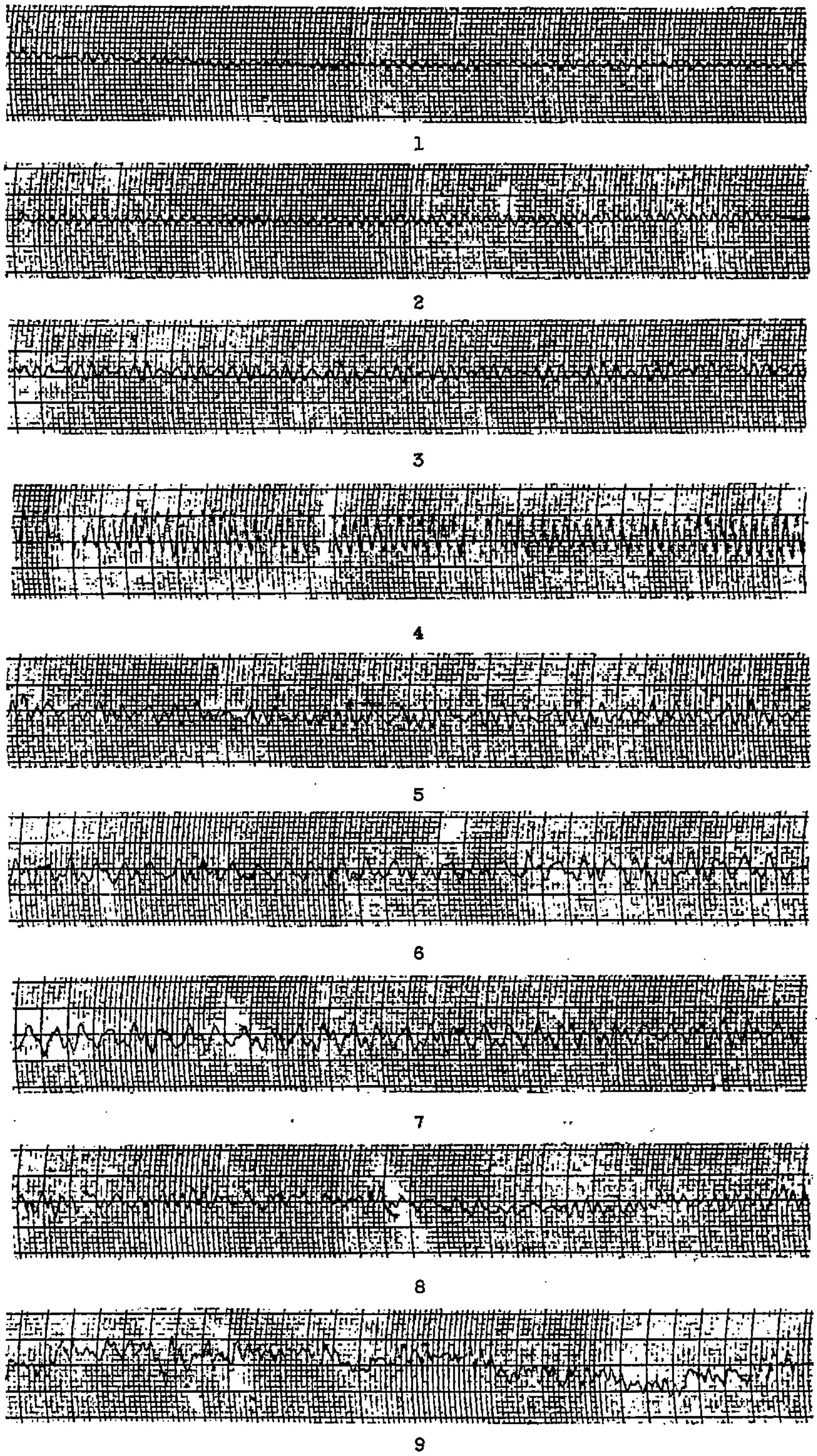


Figure 23. - Pressure oscillation traces in 16-inch ram jet at various mass-flow ratios using kerosene - propylene-oxide fuel blend. Free-stream Mach number, 1.58.

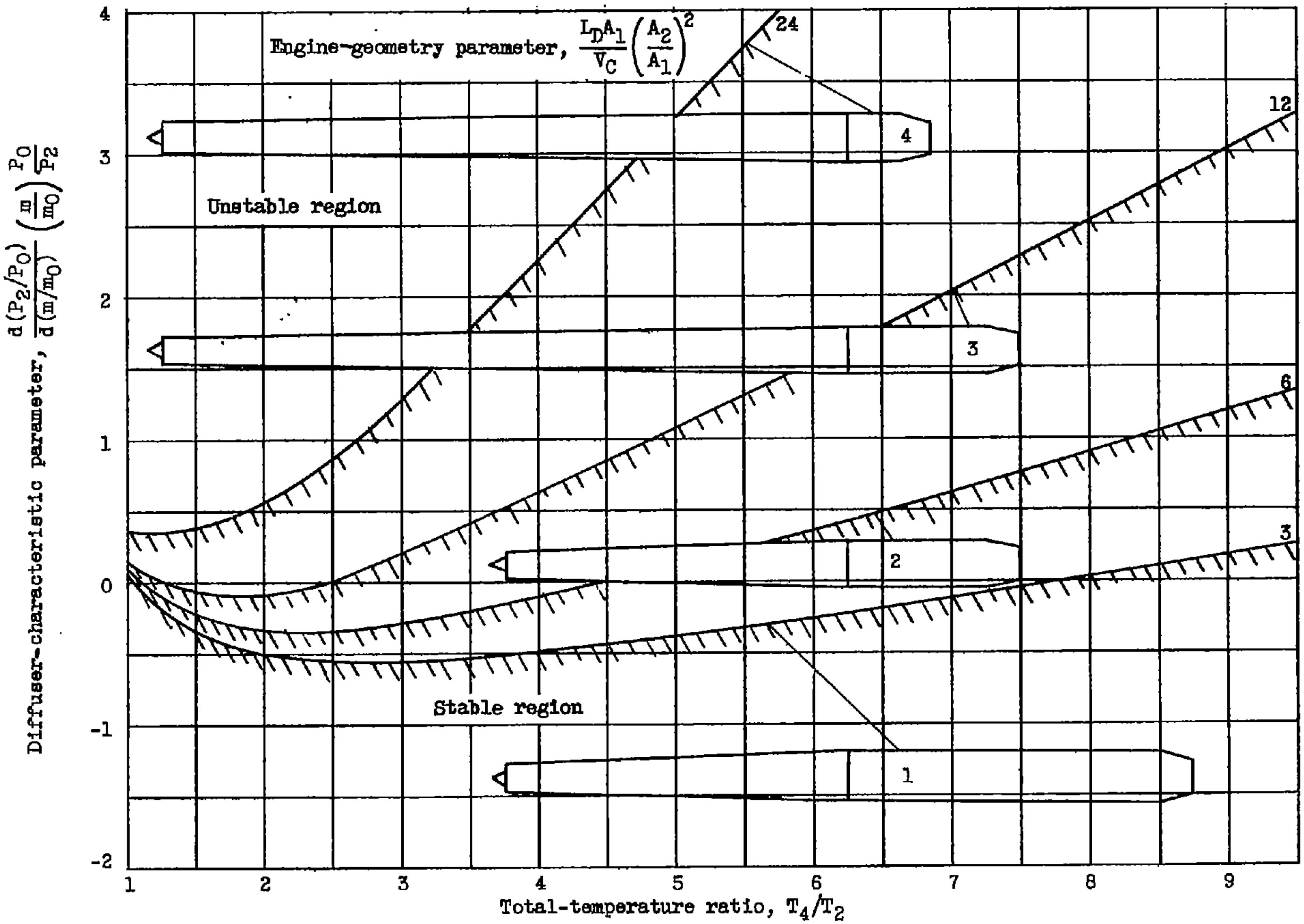
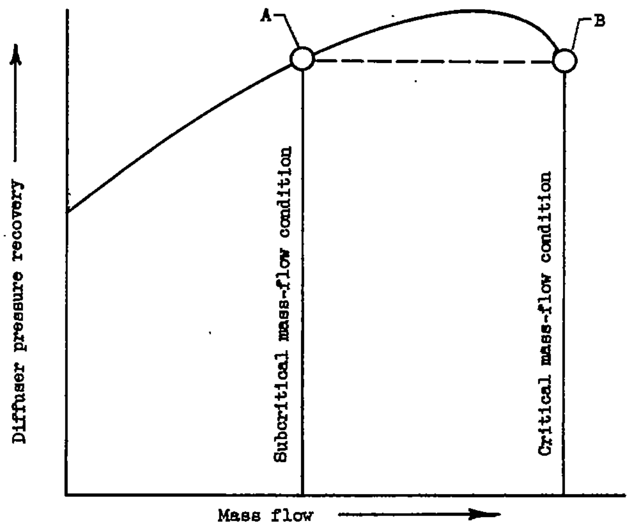
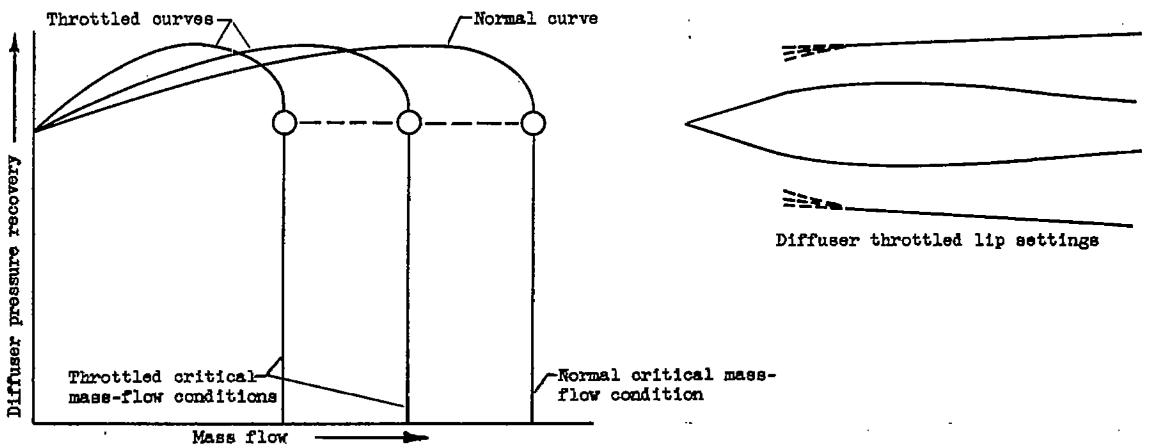


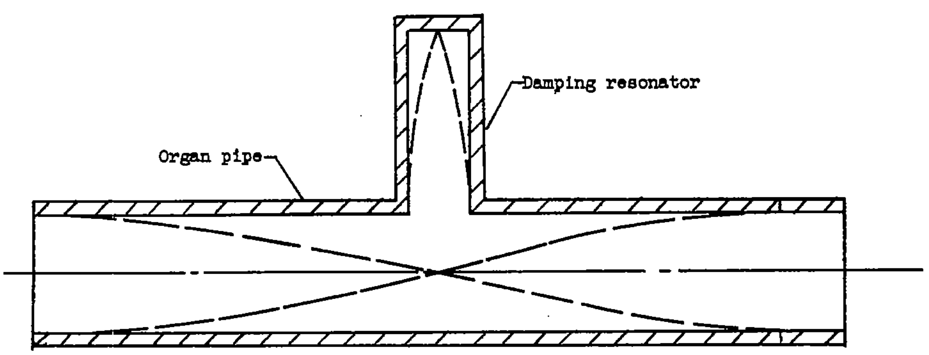
Figure 24. - Ram-jet design trends for improved resonance stability.



(a) Mass-flow bleed-off system for pulsation-free operation.



(b) Diffuser mass-flow throttling system for pulsation-free operation.



(c) Organ-pipe resonance damping by means of attached damping resonator.

Figure 25. - Illustrations of some methods for obtaining pulsation-free flow through ram jets.

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